STANDARDS DEVELOPMENT BRANCH OMOE

RECLAMATION OF ACIDIFIED LAKES NEAR SUDBURY, ONTARIO

June, 1975

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1975

Ontario

Ministry of the Environment

The Honourable
William G. Newman,
Minister

Everett Biggs,
Deputy Minister

Date Due

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Reclamation of Acidified Lakes near Sudbury, Ontario

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June, 1975

ABSTRACT

As part of the Ministry of the Environment lake reclamation program, $Ca(OH)_2$ and $CaCO_3$ were used to artificially offset acidic conditions, re-establish buffer systems and reduce heavy metal levels in two low pH lakes near Sudbury, Ontario. Middle and Lohi Lakes were treated in the fall of 1973 and monitoring continued into 1975. The lakes upstream of each treated lake, Hannah and Clearwater respectively, were monitored as controls. It was determined that a combination treatment ($CaCO_3$ plus $Ca(OH)_2$ as opposed to $Ca(OH)_2$ only) provided a more stable buffer system and maintained improved water quality for a longer period of time. Microbial and phytoplanktonic populations showed a positive response to treatment, increasing in standing stock. Zooplanktonic and zoobenthic populations declined, probably due to the lethally rapid pH change. Numbers are expected to increase in future in response to the improved water conditions and increased food availability.

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The field and technical work was carried out with the able assistance of B. Cave and J. Jones. L. Maki and W. Rozenberg receive thanks for zoobenthos collections in 1973. C. Chun and C. Turner helped in the field periodically, and did an excellent job on the chemical analyses.

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Phytoplankton identification was carried out by staff of the Plant Taxonomy and Technical Support Unit, zooplankton by B. Cave, 1973 zoobenthos by L. Maki and W. Rozenberg, 1974 zoobenthos by M. Paylor. Dr. O.A. Saether (Freshwater Institute) kindly identified the Chironomidae to species. The secretarial staff are thanked for enduring our constant demands and J. Jones is acknowledged for his fine draftsmanship on the text figures.

M. Michalski provided the initial guidance and experimental design for the project. Lastly, Dr. P.J. Dillon deserves special mention for his continuing input into the project and his role as editor of this report.

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SUMMARY AND CONCLUSIONS

1. Liming has proven to be a simple, relatively inexpensive tool to neutralize acidic lake conditions and re-establish a weak buffer system in a controlled and predictable manner in the lakes investigated to date.
2. The technique significantly reduces copper and nickel levels in the water column, probably by a precipitation mechanism.
3. Treatment with calcium carbonate ($CaCO_3$) in addition to calcium hydroxide ($Ca(OH)_2$) provides a carbonate reservoir and maintains a more stable buffer system. The carbonate-treated lake (Middle) continues to maintain a neutral pH and lower copper and nickel levels than Lohi Lake ($Ca(OH)_2$ only added).
4. Open water microbial populations generally showed a rapid, positive response to lime addition in both treated lakes. Sediment populations remained relatively constant.
5. Phytoplankton standing stocks showed a positive response to the improved water quality, increasing fivefold in the treated lakes during the summer following liming as compared to a doubling in the control lakes. A shift in species dominance from green algae and flagellates to yellow green algae (Chrysophceae) occurred indicating a return to a situation more typical of unstressed Shield lakes. A similar shift occurred in control lakes but to a lesser extent.
6. Zooplankton standing stocks declined in the treated lakes the summer following liming, probably due to a lethally rapid pH change at the time the dominant zooplankton, Cladocera, was laying overwintering eggs. This reduced the following spring cohort. However, as sufficient food is available, it is expected that zooplankton numbers will increase in following seasons.
7. Similarly, the zoobenthic population decline in the treated lakes is probably due to an interruption of the life cycle of the dominant organism, midge (Chironomidae), caused by the sudden pH change. It is expected that numbers will return in response to available food and improved water conditions.
8. Evidence from enclosure studies indicates that the biological recovery of the treated lakes may be speeded by artificial fertilization with phosphorus.

INTRODUCTION AND BACKGROUND

In recent years evidence has pointed to the decline of fish populations in the greater Sudbury area. Because both sport and non-sport fisheries have declined, overfishing cannot be considered solely responsible. It has been hypothesized that a decrease in lake pH is the cause because in most cases a drop in pH coincide with the decline (Beamish and Harvey, 1972).

Data from Gorham and Gordon (1960) and Johnson and Owen (1966) showed the existence of abnormally low pH and high sulphate levels in lakes in the immediate vicinity of Sudbury not obviously affected by acidic mine tailing runoff. An Ontario Water Resources Commission (1971) report presented data indicating that lakes of unusually low pH and high heavy metal concentrations existed up to 40 miles distant from Sudbury, with those in a N.E. - S.W. direction showing the greatest levels. Beamish and Harvey (1972) and Conroy, Jeffries and Kramer (1974) confirm the widespread nature of the problem.

Since many of the affected lakes are in remote areas where no mine tailing effluents exist, it must be assumed that the changes in lake chemistry are a result of atmospheric input. The fact that precipitation can exert an important influence on the ionic chemistry of lakes has been documented by many workers around the globe (Eriksson 1955; Gorham 1958, 1961; Gorham and Gordon 1960; Oden and Ahl 1970; Schindler and Nighswander (1970).

Lakes on the Canadian Shield, especially those located on quartzite bedrock common around the Sudbury area, typically have low mineral content because of the insoluble nature of the rock. Their buffering capacity is correspondingly low and the lakes are sensitive to even slight acid loadings. Once the natural buffering capacity of these lakes is depleted, the pH will fall rapidly. Even if atmospheric input were halted, the affected lakes may not readily recover by natural processes. The objective of the lake reclamation experiments is to artificially re-establish a buffer system in selected acid lakes such that the water quality is suitable for a reproducing fish population. If feasible, these experiments would set a precedent for further reclamation projects on similarly affected lakes. This paper presents the results of the first two years of treatment with neutralizing substances of Middle Lake and Lohi Lake.

The addition of neutralizing agents to alter lake water chemistry with a view to improving productivity is not a new technique. However, much of the early work was carried out on humic lakes with high organic matter but low productivity. Ness (1949) presented an historical account of lime treatment procedures used in central Europe beginning over a century ago. Because biological productivity and lake alkalinity were found to be directly related, it was assumed that productivity could be enhanced by artificially increasing the alkalinity of the lake. Ball (1948), Moyle (1949), Thomaston and Zeller (1961) and others experimentally demonstrated the validity of this relationship.

Hasler, Bryndelson and Helm (1951) and Waters (1956) conducted experiments emphasizing the changes in lake chemistry after liming which provide background data for the Sudbury experiments. Changes in pH, alkalinity, dissolved oxygen and Secchi depth indicated improvements in water quality and increases in productivity. Bowling and Busbee (1964) investigated the long-term changes in the number of benthic organisms as a result of lime application using three Georgia farm ponds. Their results demonstrated that the benthos tended to show the same increase in productivity with lime application as did phytoplankton. Two neutralization experiments have been conducted in the Sudbury area. In 1958 Morris attempted to neutralize Clearwater Lake with crushed limestone. However, 1973/1974 data for this lake indicate an extremely acidic condition suggesting that the long-term effects of a single dose operation are minimal. Falconbridge Nickel Limited have been neutralizing tailing wastes by mixing them mechanically with crushed limestone prior to discharge into Moose Lake. To date the process seems to be restoring the chemical water quality of the lake.

In summary, previous lime treatment experiments have generally shown that the technique can provide many beneficial changes in the water quality of lakes. The Sudbury experiments were conducted with this expectation.

DESCRIPTION OF STUDY AREA

Following a field survey of 10 lakes in the immediate vicinity of Sudbury (Appendix I) conducted in June 1973, two pairs of lakes were selected for experimentation; Hannah - Middle and Clearwater - Lohi. Hannah and Clearwater, the upstream lakes of each pair, served as control systems while reclamation efforts were carried out in the two downstream lakes, Middle and Lohi. All lakes drain via the Vermillion River to the Spanish River and ultimately into the North Channel of Lake Huron. For a more detailed location see Fig. 1.

All lakes lie on Precambrian Shield rock. The predominant bedrock for lakes Hannah and Middle is Wanapitei quartzite with mafic intrusions of gabbro and metagabbro in the Middle Lake drainage basin. The Clearwater drainage basin is made up of Grenville gneiss and migmatite with mafic intrusions and Wanapitei quartzite comprising the remainder. The drainage basin of Lohi downstream of Clearwater is composed mostly of Wanapitei quartzite with mafic intrusions (see Fig. 2). Table 1 outlines the chemical composition of the major minerals found.

Shoreline vegetation for the Hannah - Middle pair is sparse whereas 20 - 50 year old stands of birch and poplar characterize the Clearwater - Lohi system. Human usage of the lakes is primarily for recreational purposes. The Hannah - Middle pair have less than 15 dwelling units each whereas Clearwater and Lohi are more heavily used with 25 - 35 units each. A complicating factor is the existence of the newly constructed Highway 17 Sudbury by-pass, which cuts through the drainage basins of Hannah and Middle Lakes.

The majority of the mineral content of lake water is often a balance between positively charged calcium and magnesium ions (hardness) and negatively charged bicarbonate ions (alkalinity) with a smaller percentage composed of positively charged sodium and potassium ions and negatively charged chloride, sulphate and nitrate ions. Bicarbonate ions help maintain near-neutral pH conditions by acting as a buffer.

The situation in the experimental Sudbury lakes deviates greatly from this norm in that the greatest percentage of the mineral content is a balance between calcium and magnesium ions and sulphate ions. The lack of bicarbonate ions means that the buffer system of the lake is essentially depleted. The excess sulphate ions are balanced by hydrogen ions, resulting in a pH decline and acidic lake water.

Figure 1: Location of Reclamation Lakes.

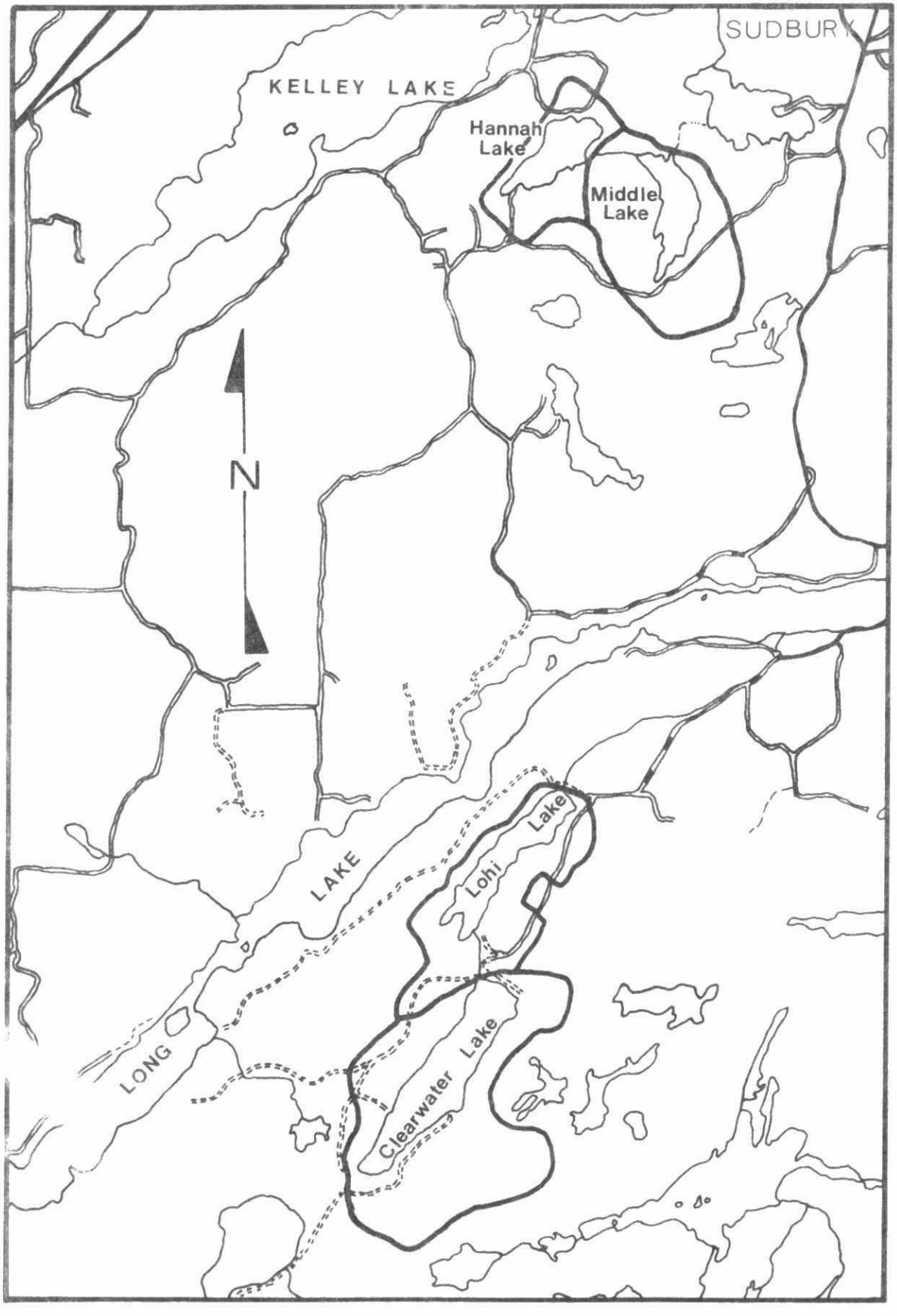
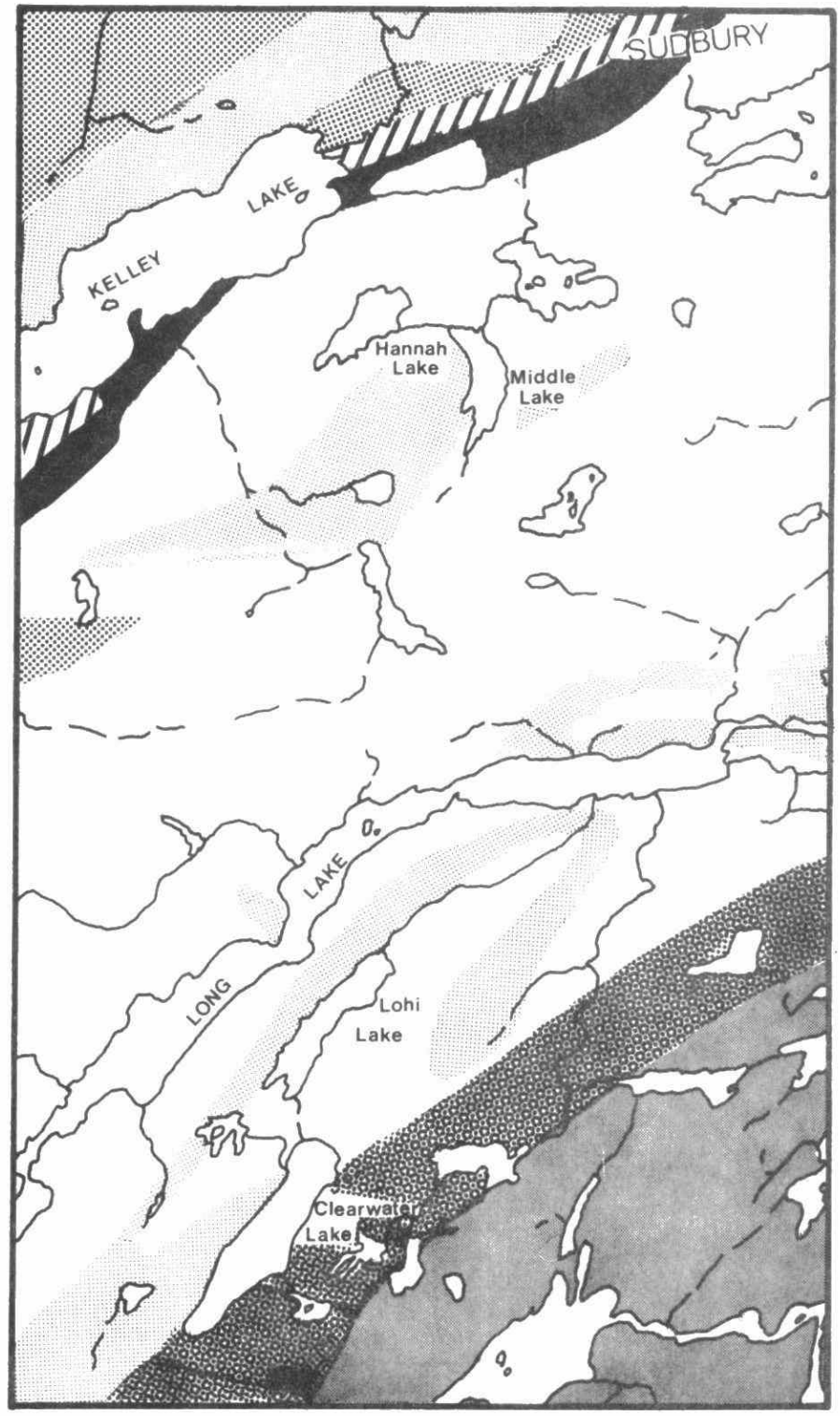


Figure 2: Bedrock Composition of Study Area.



LEGEND

FIGURE 2. BEDROCK COMPOSITION IN STUDY AREA

UNDIFFERERENTIATED GRANITIC ROCKS

GABBRO, METAGABBRO

RAMSEY LAKE CONGLOMERATE

GNEISS, MIGMATITE, GRANITIC INTRUSIONS

WANAPITEI QUARTZITE

McKIM PELITES

PELITIC AND PSAMMITIC METASEDIMENTS,

UNDIFFERENTIATED

Table 1: Chemical Composition of Major Minerals Comprising Drainage Basin Bedrock.

Rock Type	Chief Mineral Composition	Chemical Composition
quartzite	quartz	silicon dioxide
gabbro	pyroxene	silicates of calcium, magnesium and iron
	plagioclase feldspar	alumino-silicates of calcium and sodium
granitic gneiss	feldspar (major component)	alumino-silicates of sodium, calcium, potassium
	quartz	silicon dioxide
	mica	sheet alumino-silicates of potassium, magnesium, iron and lithium
	amphibole	silicates of calcium, iron, aluminum and magnesium
	garnet	alumino-silicates of calcium, iron, magnesium and aluminum
migmatite	feldspar	as above
	quartz	as above
	amphibole	as above
	biotite	sheet alumino-silicates of potassium, iron, aluminum and magnesium

Morphometric data for the lakes are summarized in Table 2. The turnover times, τ_w in years, for the experimental lakes are estimated to be 1.6 for Lohi and 1.9 for Middle, suitable for reclamation because the rates are slow enough to prevent immediate washout of the lime. Lake morphology and morphometry are diagrammed in Appendix B.

METHODS

1. Liming

a) Choosing the Neutralizing Agent

The process of choosing the appropriate chemical neutralizing agent involves consideration of the following criteria:

1) It must be readily available in large quantities.
2) It should be relatively inexpensive.
3) It must be safe to handle and store using conventional safety precautions and equipment.
4) It should have a high neutralization potential; i.e. a small quantity of chemical should be capable of neutralizing a large quantity of water.
5) The addition of a known quantity of chemical must produce a predictable change in pH. This is critical if pH sensitive organisms are already living in the lake.
6) It must be amenable to a relatively simple application technique such that a large quantity of chemical could be applied in a short period of time with a minimum of manpower and equipment.
7) It must provide for a natural deficiency in the lake water i.e. it should be a normal component of the lake's buffer system.
8) It should not initiate any significant ion exchange processes in the lake sediments which could impair the quality of the lake water.
9) It must not add any extraneous contaminants to the lake water.

Cost and availability eliminates most possibilities, such as sodium hydroxide, potassium hydroxide, sodium carbonate, sodium bicarbonate, and magnesium oxide. Stipulation that the additive provide for a natural deficiency in the lake water further limits the choice to a type of calcium compound.

Three calcium compounds fit the cost and availability criteria; calcium oxide, calcium hydroxide and calcium carbonate. Calcium carbonate is non-corrosive but approximately 30% reactive. Furthermore, it becomes increasingly

Table 2: Morphometric Data for Reclamation Lakes.

Parameter	Hannah	Middle	Clearwater	Lohi
Co-ordinates				
Latitude	81° 02' W	81° 01' W	81° 03' W	81° 06' W
Longitude	46° 26' N	46° 26' N	46° 22' N	46° 23' N
Altitude (m above sea level)	289.6	289.6	285.0	282.0
Approximate Distance from Smelter (km)	4	5	12	10
Length of Shoreline (km)	2.7	3.2	4.7	4.2
Drainage Basin Area (km^2)	.94	2.6	3.2	4.7
Lake Area (km^2)	.18	.21	.77	.29
Lake Volume ($m^3 \times 10^6$)	1.4	2.2	6.9	3.1
Maximum Depth (m)	7.5	14	19	17
Mean Depth (m)	5.9	9.4	8.8	9.2
Turnover Time (τ_w in years)	3.6	1.9	5.3	1.6

inefficient at pH values > 4 because the precipitation of insoluble reaction products tends to seal off particle surfaces unless vigorous mechanical agitation is applied. Neutral pH values are thus difficult to achieve and maintain using this compound. However, surplus calcium carbonate could assist in maintaining near-neutral conditions over extended periods of time because the carbonate would act as a buffer.

Calcium oxide is extremely corrosive and generates considerable heat upon reaction with water making storage and handling difficult. Calcium hydroxide is less hazardous and does not generate heat upon contact with water. It has a reactivity estimated in excess of 97% thus making pH endpoints > 10 possible and necessitating careful dosage control.

Further experiments were conducted to examine whether the treatment chemical would effect any release of soluble chemical constituents from lake sediments. Eighteen 40 gm portions of wet sediment from the deep water location of Middle Lake were mixed with 100 ml distilled water and the pH values recorded. This solution was titrated with .01 M calcium hydroxide until a stable pH of 8 was achieved (61 ml of titrant). Sixty-one ml of .01 M KOH, NaOH, MgO, Na_2CO_3, NaCl and $CaCl_2$ were then added to the remaining sediment solutions respectively. The final volume of each solution was adjusted to 200 ml with distilled water, allowed to stand for 24 hours and the pH again measured. Each solution was filtered and divided into two portions, one analyzed for sulphate, free ammonia, nitrate, nitrite and soluble phosphorus, the other acidified with nitric acid and analyzed for Ca, Mg, Fe, Zn, Cu, Ni, Mn and Cr. From the results displayed in Table 3, it can be seen that calcium hydroxide generates the least chemical release.

Upon consideration of the criteria, the following experimental procedure was decided upon to offset acidic conditions and provide a buffer system. Lohi Lake would be treated with calcium hydroxide only and Middle Lake would be treated with calcium hydroxide and calcium carbonate.

b) Chemical Dosages

An estimate of the calcium hydroxide dosage was obtained by titrating representative lake water (5 stations/lake) and sediment (21 stations on Middle, 26 on Lohi) samples with a standard calcium hydroxide solution to a stable pH endpoint of 8.0 and projecting the quantity of titrant used over the entire lake. The pH endpoint of 8.0 was chosen because lake water at this pH would provide for

Table 3: Chemical Release from Lake Sediments caused by Different Treatment Chemicals.

	H_2O	$Ca(OH)_2$	KOH	NaOH	MgO	Na_2CO_3	$NaHCO_3$	NaCl	$CaCl_2$
Initial pH	6.21	6.20	6.18	6.09	5.93	6.22	5.94	6.02	6.18
	6.18	6.21	6.05	6.07	6.01	6.04	6.10	6.05	6.07
Final pH	6.22	7.89	7.53	8.12	7.18	7.71	6.86	5.75	4.84
	6.21	7.91	7.52	7.96	7.29	7.66	6.82	5.79	4.89
$SO_4^=$	60	75	120	130	120	140	150	200	140
	75	80	140	150	130	170	160	190	150
Free Ammonia as N	1.0	.60	3.9	6.0	2.4	6.0	1.5	2.4	2.9
	.60	1.3	4.4	5.0	1.1	6.0	1.5	2.2	3.6
NO_2^- as N	.12	.30	.35	.44	.36	.60	.30	.03	.02
	.14	.36	.43	.41	.34	.70	.29	.03	.02
NO_3^- as N	.25	.60	.65	1.1	.75	1.8	.65	.05	<.05
	.40	.65	1.1	1.1	.75	2.0	.60	.05	<.05
Soluble Phosphorus	.36	.90	1.1	3.2	.90	2.4	.70	.04	<.005
	.38	.60	1.3	2.1	.90	2.8	.70	<.005	<.005
Ca	28	70	18	18	28	33	18	60	400
	28	50	22	25	24	21	17	65	410
Mg	5.0	5.5	2.5	2.5	45	5.0	3.1	14	16
	5.5	5.5	3.1	3.1	41	3.1	1.9	14	15
Fe	1.9	6.5	8.0	12	5.5	14	3.8	5.5	16
	1.8	6.5	11	11	4.9	13	4.3	4.8	15
Zn	<.25	<.25	<.25	<.25	<.25	.35	<.25	.85	1.1
	<.25	<.25	.25	.30	<.25	.35	<.25	.85	1.3
Cu	.80	2.3	2.9	3.9	2.4	3.8	2.0	2.8	2.9
	1.1	1.4	3.9	4.1	2.3	5.5	2.0	2.9	2.9
Ni	.80	1.0	1.4	2.0	1.1	1.5	.95	6.5	9.0
	1.5	1.2	1.9	2.1	1.1	2.7	1.4	6.5	11
Mn	.40	.30	.25	.20	.35	.35	.30	2.4	7.0
	.50	.25	.20	.30	.35	.30	.30	2.5	6.5
Cr	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1

All results are reported as µg of material per gram of wet sediment.

efficient sediment neutralization. The volume of sediment to be neutralized was calculated by making two assumptions. The lake surface area was increased by 20% to estimate the bottom area and the thickness of the reactive sediment layer was arbitrarily chosen as 5 cm.

Because the neutralization of the lake water would occur rapidly, the entire water dosage was added in one application. However, the sediment neutralization take place slowly at the expense of the hydroxide in the lake water necessitating additional incremental dosages to maintain pH control. Sediment lime usage was determined by monitoring the pH drop in lake water and the necessary incremental additions to maintain lake water neutrality were calculated by periodic titrations.

c) Application of Chemicals to the Lakes

Chemicals were applied to the lakes via a flash slurrying device, consisting of a small bowl-like mixing chamber and several lengths of pipe installed on a boat. Lake water was tangentially injected into this chamber using a high pressure fire pump, while dry chemicals were simultaneously fed into the chamber via a hopper. A larger diameter pipe then discharged the slurry into the backwash of the boat. Approximately 7,260 kg (8 tons) could be applied to a lake in an average working day using one 16' boat and a five man crew (two onshore, two loading hopper on boat, one driver). (Figure 3).

The quantity of chemicals applied to the lakes is presented in Table 4. Calcium hydroxide dosages were based on a set of lake water titrations as previously described. Fifteen additional tons of calcium carbonate were added to Middle Lake after the neutralization with calcium hydroxide was completed. The total calcium carbonate dosage was chosen arbitrarily but the applied dosage is still well under the projected dosage. No immediate pH change was observed in the lake as a result of the calcium carbonate addition. Since Lohi Lake did not receive any calcium carbonate, comparison of the pH level in the two lakes over an extended period of time would indicate whether or not calcium carbonate can play a pertinent role in stabilizing the chemical treatment process. Theoretically, Middle Lake should be able to maintain a neutral pH longer than Lohi Lake.

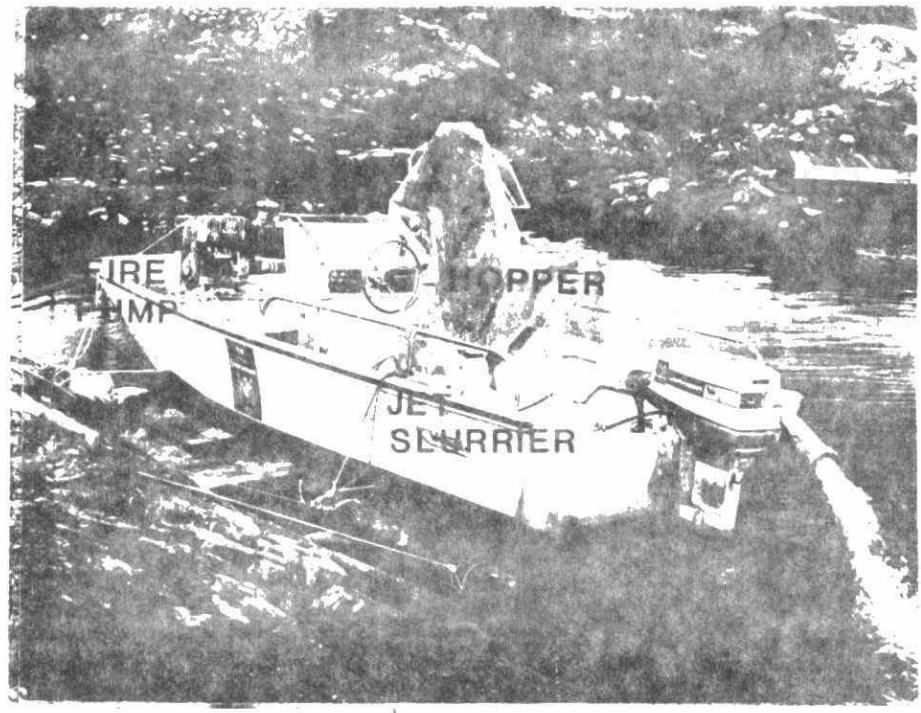
d) Quality of Treatment Chemicals

The possibility of introducing trace contaminants into the lakes by application of contaminated treatment chemicals was evaluated via chemical assays on both the calcium hydroxide and the calcium carbonate powder used in

TABLE 4: Summary of Chemical Quantities and Scheduling

DATE	CHEMICAL APPLIED	DOSAGE APPLIED kg (tons)	
		Middle Lake	Lohi Lake
25/9/73	$Ca(OH)_2$	2,721 (3)	- -
26/9/73	$Ca(OH)_2$	5,442 (6)	- -
28/9/73	$Ca(OH)_2$	907 (1)	- -
3/10/73	$Ca(OH)_2$	7,256 (8)	- -
16/10/73	$Ca(OH)_2$	- -	9,070 (10)
17/10/73	$Ca(OH)_2$	1,814 (2)	4,535 (5)
29/10/73	$Ca(OH)_2$	1,814 (2)	- -
31/10/73	$CaCO_3$	7,256 (8)	- -
1/11/73	$CaCO_3$	6,349 (7)	- -
2/11/73	$Ca(OH)_2$	- -	4,535 (5)
5/7/74	$Ca(OH)_2$	- -	4,082 (4.5)
	$Ca(OH)_2$	19,954 (22)	22,222 (24.5)
	$CaCO_3$	13,605 (15)	- -

Figure 3: Application of Lime to the Lake.



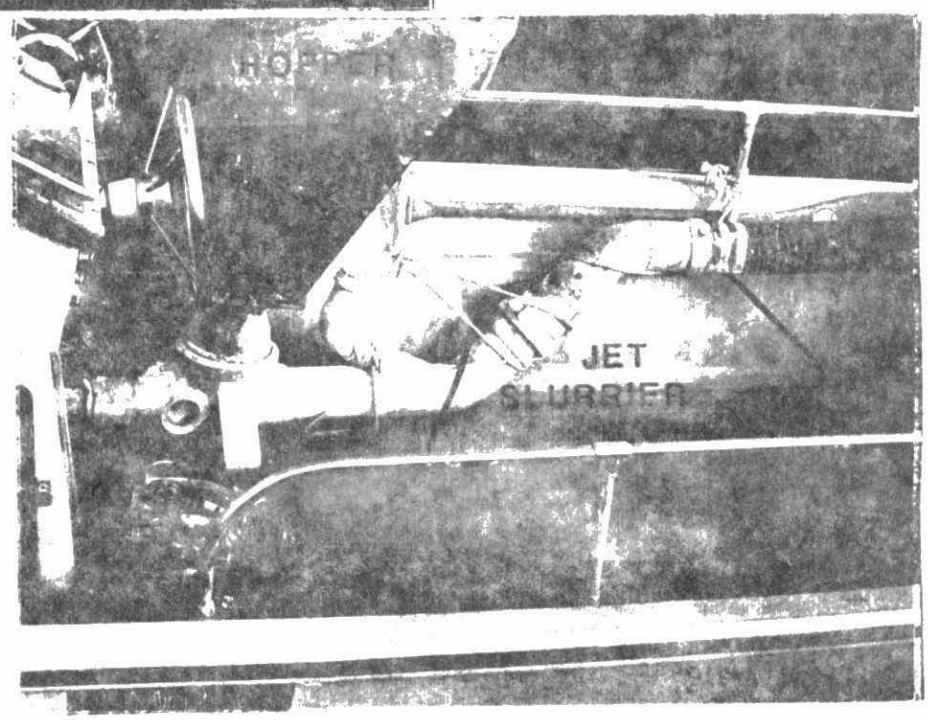


TABLE 5: Quality of Treatment Chemicals

			Projected increases in lake water based on known dosages (mg/l)			
	Direct Assay on $Ca(OH)_2$	Direct Assay on $CaCO_3$	Lohi $Ca(OH)_2$	Middle $Ca(OH)_2$	Middle $CaCO_3$	
Calcium	48.7%	38.0%	2.4	5.3	2.8	
Magnesium	3.37%	3.40%	.024	.036	.025	
Phosphorus	<.2 mg/g	<.2 mg/g	<.00014	<.00022	<.00015	
Nitrogen	<.5 mg/g	<.5 mg/g	<.00036	<.00054	<.00037	
Chromium	<10 µg/g	<10 µg/g	<.0000072	<.000011	<.0000076	
Zinc	39.2 µg/g	71.1 µg/g	.000028	.000042	.000052	
Copper	13.1 µg/g	12.4 µg/g	.0000096	.000014	.0000092	
Nickel	37.4 µg/g	26.4 µg/g	.000027	.000041	.000019	
Manganese	86.1 µg/g	62.8 µg/g	.000064	.000092	.000046	
Iron	571 µg/g	504 µg/g	.00040	.00060	.00037	

the treatment procedure.

The results of these assays are expressed in terms of the contaminant concentration in the treatment chemical as well as the projected contaminant concentration in the lake water after treatment (see Table 5). In every case, the chemical additive is an insignificant source of contamination.

2. Field Sampling Techniques

The same techniques were employed in 1973 and 1974 except where noted. Appendix B summarizes the frequencies of sampling. Sampling locations are diagrammed in Appendix C.

a) Physical Parameters

The deepest point on each lake, marked with a permanent buoy, was chosen as the main sampling station. A temperature profile was taken at 0.5 m intervals with a YSI telethermometer. Water transparency was measured with a standard 9 inch diameter Secchi disc as outlined in Hutchinson (1957). The euphotic (light) zone was chosen as twice the Secchi depth (Vollenweider 1969). In 1973, the lakes were sounded, contour maps drawn up and the surrounding vegetation catalogued.

b) Chemical Parameters

Two techniques were used to collect water samples for the parameters listed in Table 6. A 6 liter van Dorn sampler was used at 1 meter below surface (1MBS) and at 1 meter above bottom (1MAB) and the contents decanted into 32 oz. Boston round bottles previously detergent washed at the M.O.E. Lab in Toronto. Group 1 parameters (Table 6) were transported to the Sudbury field lab for analysis. For Group 2 parameters, preservative was added as indicated and the samples shipped to Toronto for analysis. Group 3 and 4 parameters were sampled with the "composite-can" technique in which a Boston Round bottle is fixed in a lead-bottom bucket. The bucket is lowered and raised through twice the Secchi depth thus taking a column sample through the euphotic zone. Group 3 parameters were fixed at the Sudbury facility. Group 4 parameters were decanted from the Boston bottles into polyethylene ones, frozen (or cooled) and shipped to Toronto for analysis.

Water samples were analyzed for oxygen at varying depths to 1MAB using the standard Winkler technique. Samples were taken at 1MBS and 1MAB and decanted into 265 ml BOD bottles for free carbon dioxide analysis at the Sudbury

TABLE 6

Group	Parameter	Bottle Type	Capacity	Preservative
1)	pH, alkalinity, hardness conductivity, calcium, magnesium	Boston Round (glass)	950 ml	
2a)	sulphate, chloride, sodium, potassium, total suspended solids, turbidity	"	"	
b)	Ni, Cu, Co, Al, Fe, Mn, As, Zn, Pb	"	"	10 ml HCl
3a)	phytoplankton	"	"	2 ml Lugol's
b)	chlorophyll a	"	"	1 ml $MgCO_3$
4a)	dissolved reactive silicates	polyethylene	500 ml	cooled
b)	nitrite, nitrate, ammonia, total Kjeldahl nitrogen, soluble phosphorus, total phosphorus	"	"	frozen

facility.

All core samples were taken with a K-B corer having a single 20 cm long plexiglass core with an inside diameter of 5 cm. The top two 5 cm, sections of the cores were separated and sent to Toronto for analysis. Cores used for profile analysis were capped at both ends with rubber stoppers, stored frozen and transported to Toronto for analysis.

Sediment traps were suspended five feet from the lake bottom at the deep water station of each lake from August to November 1973. The traps were basically composed of a funnel (20 cm mouth diameter) leading into a 1 liter container. At the end of the time period the traps were pulled up, the containers sealed, frozen and shipped to Toronto for analysis.

c) Biological Sampling

i) Microbiology: For the time periods shown in Appendix B water samples were taken by Reclamation staff in duplicate at each station (three per lake in 1973, two in 1974) by attaching a 250 ml Nalgene bottle to a 10 foot aluminum pole and dipping horizontally at 1 MBS. Water samples were taken at 1 MAB at each station with a modified piggy-back bulb sampler which filled a pre-sterilized evacuated 250 ml bulb automatically. Sediment samples were taken with the K-B corer previously mentioned and the top 5 cm decanted into a 125 ml Nalgene bottle.

All microbiological samples were kept on ice, transported to the Sudbury airport, flown to Toronto and analyzed within 24 hours of sampling.

Maclean Lake (classed as eutrophic was sampled in 1973 and 1974. Minnow (eutrophic and Harp (oligotrophic) Lakes were sampled in 1974 for comparative purposes.

Water samples were routinely analyzed for total aerobic heterotrophs (direct plate count) acidophilic bacteria, and yeasts. At various time intervals levels of blue-green algae, sulphate reducers, sulphur oxidizers, and nitrifiers were also examined. Sediments were tested for total aerobic and total anaerobic heterotrophs and occasionally for sulphate reducers, sulphur oxidiers, and nitrifiers.

The S and N bacteria were enumerated using the MPN (most probable number) method, with triplicate replication for each dilution. Yeasts and blue-green levels were determined by the membrane filtration (MF) methods. Analysis for all remaining parameters was completed by a modified spot plate method (Thompson and Croll, 1974).

ii) Primary Production

Primary production was measured weekly using the ^{14}C technique as outlined in Michalski, Johnson and Veal (1973) with the following modifications. One half ml of radioactive $NaH\ ^{14}CO_3$ was injected into 265 ml BOD bottles by autosyringe. The bottles were set at six depths (Michalski et al 1973) shortly after sunrise and left for four hours (Schindler and Fee, 1973). After this time, 10 ml of water were removed and 10 ml of $HgCL_2$ were added to arrest biological activity.

The water was filtered through 0.45 μ millipore paper under 40 cm Hg pressure at the Sudbury facility. The paper was dried under an infrared lamp, stored in a vial containing scintillation solution (PPO/POPOP in toluene) and transported to Toronto for counting on a Packard Tricarb Liquid Scintillation Spectrophotometer.

At each sample depth, a 190 ml Prince of Wales bottle was filled for inorganic, organic and total carbon analysis.

iii) Phytoplankton and Chlorophyll a

Phytoplankton and chlorophyll a samples were collected weekly at the deepwater stations by lowering a weighted 32 oz bottle with a restricted opening through the euphotic zone. Phytoplankton samples were preserved with two ml of Lugol's in the field. One ml of $MgCO_3$ was added to the chlorophyll samples in Sudbury.

The phytoplankton sample was preconcentrated in Sudbury from 500 ml to 25 ml by allowing the plankton to settle out by gravity. Bi-weekly samples were counted (a.s.u. ml^{-1}) and identified in Toronto (see taxonomy Reference marked **).

The chlorophyll samples were filtered through .45 μ millipore paper under 40 cm Hg pressure in Sudbury. The papers were refrigerated in opaque Petri dishes and transported to Toronto for analysis.

iv) Zooplankton

One vertical haul was taken from 1 MAB at each deep water station with a Wisconsin net (mouth diameter 11 cm #20 net mesh size 76 μ). The sample was washed into a 4 ounce jar, preserved with 1 ml formaldehyde/ounce of water and stored. In Toronto, a subsample of 15% of the total volume was withdrawn, identified and counted under 10X magnification using Ward and Whipple (1966 and Pennak (1953). For rare species, the entire sample was examined.

v) Benthic Macroinvertebrates

In 1973, 30 samples were taken per lake from August 15 to 17, using a 6" x 6" x 6" Wildco-Ekman dredge. Using two transects, 20 samples were taken from the long axis, and 10 from the short axis (Appendix C). Each haul was emptied into a sieve bucket (560 μ = #30 brass mesh) and swirled in the lake until free of mud. The debris and organisms were decanted into 16 ounce jars, returned to the Sudbury lab, hand-picked and counted. Keying was done down to Family (except Oligochaeta) using Pennak (1953). The organisms were finally stored in 70% ethanol.

In 1974 the sampling effort was increased to 50 samples per lake using a 9" x 9" x 9" Wildco-Ekman dredge. Two new transects of 10 stations each were added to the previous transects. With the aid of the Ministry of Natural Resources, sampling was done from August to October 1974 as in Table 7.

Table 7: Sampling Dates and Staff for Benthic Sampling 1974.

Lake	Dates	Staff Performing Sampling/Picking
Middle	August 21-28, 1974	MNR
Hannah	August 29 - September 5	MNR
Lohi	September 13-19	MOE (Intensive Monitoring)
Clearwater	October 3-10	MOE (Reclamation)

The same sieving equipment and picking techniques were used as in 1973. MNR staff preserved the organisms in alcoholic Bouin's solution which was later transferred to 70% ethanol. Identification was to the same level as in 1973 using Pennak, (1953), Ross (1972) and Johannsen (1969). In 1974, field notes were made as to weather and sampling conditions, appearance of the mud and major life forms found.

vi) Fish

From August 8th to 13th, 1972 staff of the Ministry of Natural Resources netted fish in the Reclamation lakes as outlined in Table 8.

Table 8: Fishing Effort on Reclamation Lakes 1972.

Lake	# Gill Nets Set	#Minnow Traps Set	Total Hours Fishing Effort	# Feet of Net Laid	Fish Caught
Middle	7	4	66 hr.	2800	0
Lohi	7	4	91 hr.	2800	0
Hannah	7	4	94 hr.	2800	0
Clearwater	10	4	213 hr.	2800	0

3. Tube Fertilization

a) Introduction

Attention was turned in 1974 to methods of increasing the standing stock of the components of the food chain within a reclaimed lake. Schindler et al (1971, 1973) have demonstrated that additions of phosphate and nitrate increased the standing crop of phytoplankton in Precambrian lakes. Smith (1969) showed that increases in zooplankton and benthos also followed fertilization. It was decided to perform a preliminary fertilization study using tube enclosures. This involved the addition of nutrients to a twenty-five foot column of water isolated within a cylindrical polyethylene tube one meter in diameter.

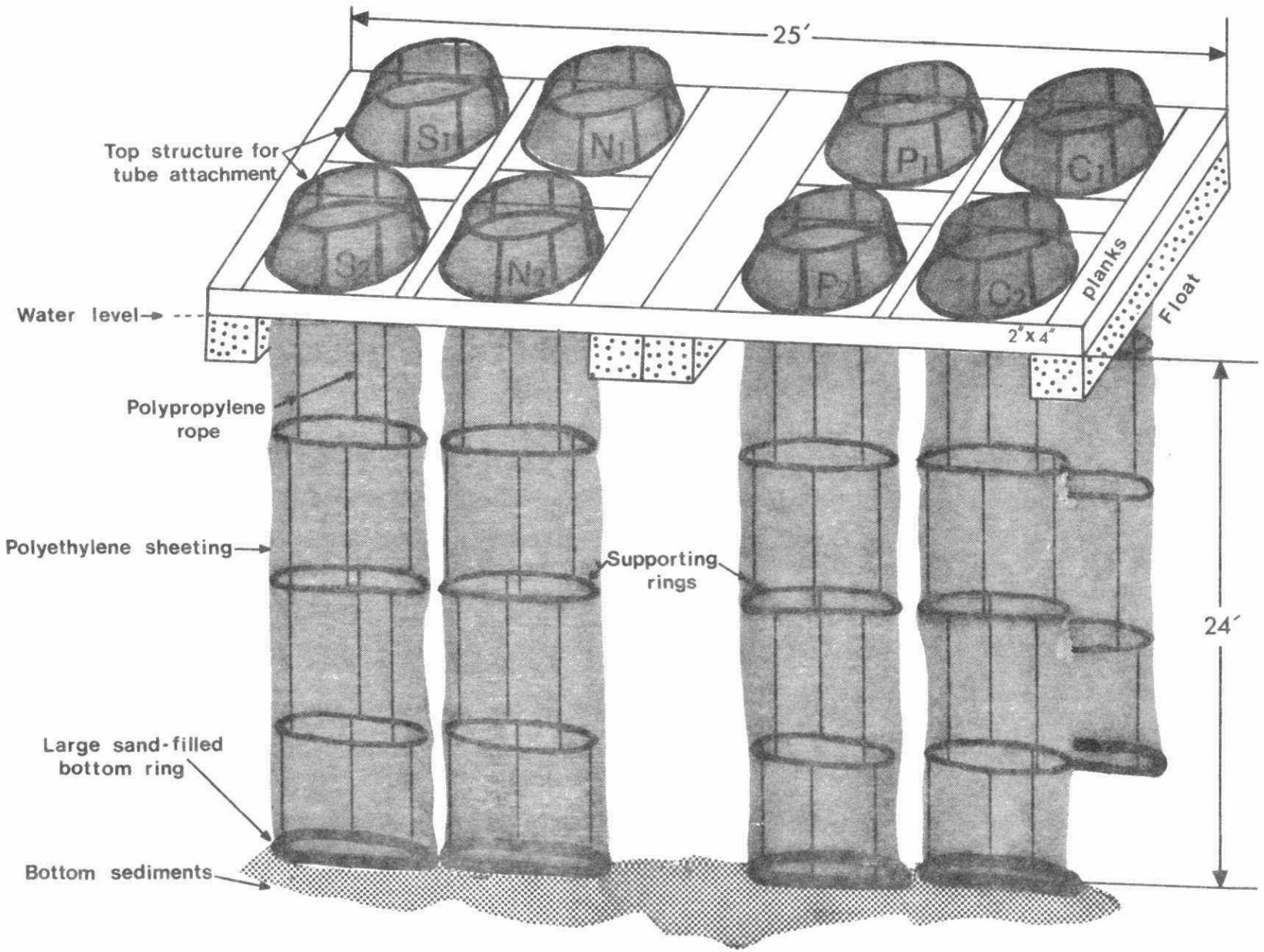
b) Experimental Design

On each of two lakes, a raft of bolted 2" by 4"'s and 3/4" plywood was set out supporting 8 tubes. Styrofoam floats were put in place under each end and the centre of the raft. Four ml gauge culindrical polyethylene sheeting on meter in diameter was used to enclose the water. The sheeting was supported by one inch polyvinyl chloride (PVC) tubing hoops and kept in the sediments by a two inch PVC tube filled with sand (Figure 4).

The raft was anchored with concrete blocks and the tubes lowered into the water and inserted into the sediments with the aid of SCUBA. Leaving a margin of one foot extra for wave action, the sheeting was wrapped around the top hoop and held in place with PVC collars.

One raft was placed on Lohi Lake (treated) and one on Clearwater (control). Each set of eight tubes was divided into four pairs, providing duplicates of: control (C), phosphorus added (P), nitrogen added (N), sewage added (S). The tubes were allowed to equilibrate for one week prior to any additions and sampled

Figure 4: Construction of the Tube Enclosures



for background information. Sampling was subsequently done weekly. Additions were made to the experimental tubes immediately after they were sampled.

c) Nutrient Additions

The additions were made according to Table 9 and were based on a tube volume of 4.8 m^3. The phosphate and nitrate were added in solution and the container was thoroughly rinsed in tube water. The sewage was added directly to the tubes and the tube water stirred with a paddle to provide some mixing.

Table 9: Concentrations of Chemicals Added to Experimental Tubes.

Tube	Chemical	Total Weekly Addition	Elemental Weekly Addition (µg/l)	Cumulative Total Added (for 10 weeks)
P	Na_2HPO_4	170 mg	7.72 µg P/l	77.2 µg/l
N	$NaNO_3$	2.24 g	76.9 µg N/l	769 µg/l
S	Secondarily Treated Sewage	7.4 l	5.5-7.7 µg P/l	63.0 µg P/l*
			34.0 µg N/l	340 µg N/l

*two batches of sewage were used, varying slightly in [P], leading to varying additions.

d) Sampling Procedures

Sampling was carried out weekly according to Appendix B from July 31 to Oct. 8, 1974. A tygon tube (internal diameter 3/4") was lowered into the enclosure, clamped at water level, raised by a line attached to the bottom end and emptied into a bucket. Microbiological sampling was carried out once on Clearwater Lake and three times on Lohi Lake using the ten foot aluminum pole at 1MBS and the modified piggy-back bulb sampler at 4 m and 7 m. All samples were refrigerated and flown to Toronto for analysis. Phytoplankton and chlorophyll a samples were taken with the tube sampler. Vertical hauls for zooplankton were taken with the aforementioned Wisconsin net on four dates, commencing in the 7th week of the experiment.

4. Lab Methodology

Samples for chemical analysis were submitted to the Ministry of the Environment laboratories in Sudbury and Toronto. Standard analytical techniques were employed as outlined in APHA (1971), Ontario Ministry of Environment (1974 in press) O'Brian (1962), Richards and Thompson (1952) and Lazrus, Hill and Lodge (1966).

RESULTS AND DISCUSSIONS

1. Physical Parameters

a) Temperature

Maximum summer surface temperatures in the lakes were 20°C to 24°C. Bottom temperatures were warm, never falling below 10°C in the summer. Clearwater and Lohi Lakes showed the dimictic thermal pattern typical of lakes of the cooler latitudes of Ontario, circulating in spring and autumn and showing temperature stratification in the summer. Hannah Lake was thermally homogenous at all times of year probably because of its shallow depth and relatively exposed shoreline. Middle Lake exhibited a thermally homogenous structure in 1973 and a dimictic pattern in 1974. Annual variations in temperature structure are not uncommon in lakes of moderate depth and occur because of annual variations in weather. Isotherms for the lakes are plotted in Figure 5.

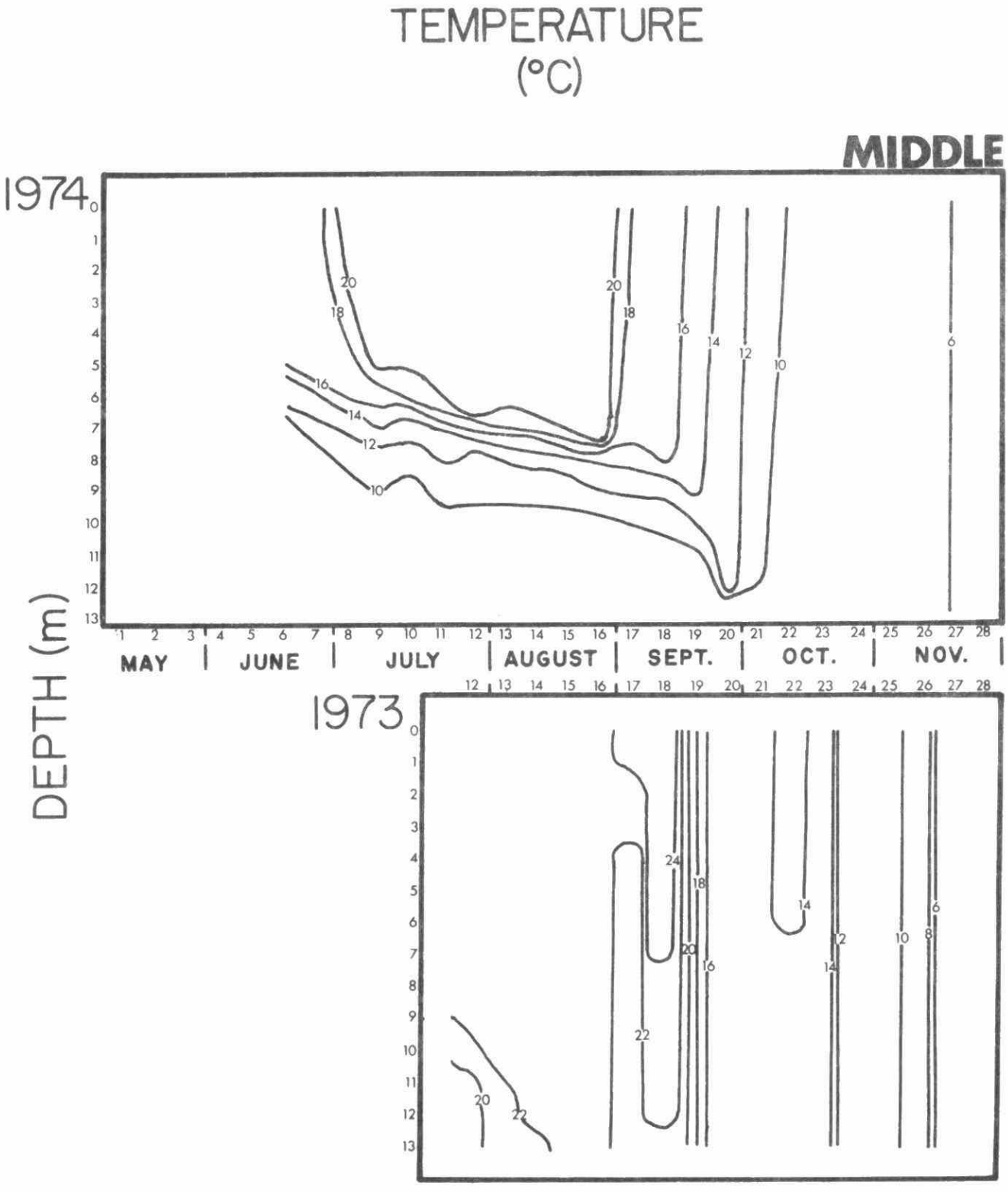
b) Light Transmission

Pre-treatment mean summer Secchi disc values for Clearwater, Lohi and Middle were 10 to 11m (Figure 6). Hannah Lake Secchi values were on lake bottom at 7m and cannot be properly assessed. These values indicate the extreme clarity and unproductive nature of the waters. Typical Secchi disc values for recreational lakes in Muskoka classed as oligotrophic (Michalski et al. 1973) are 8.1m (Joseph Lake), 7.1m (Kennisis Lake) and 6.3m (Lake Rosseau).

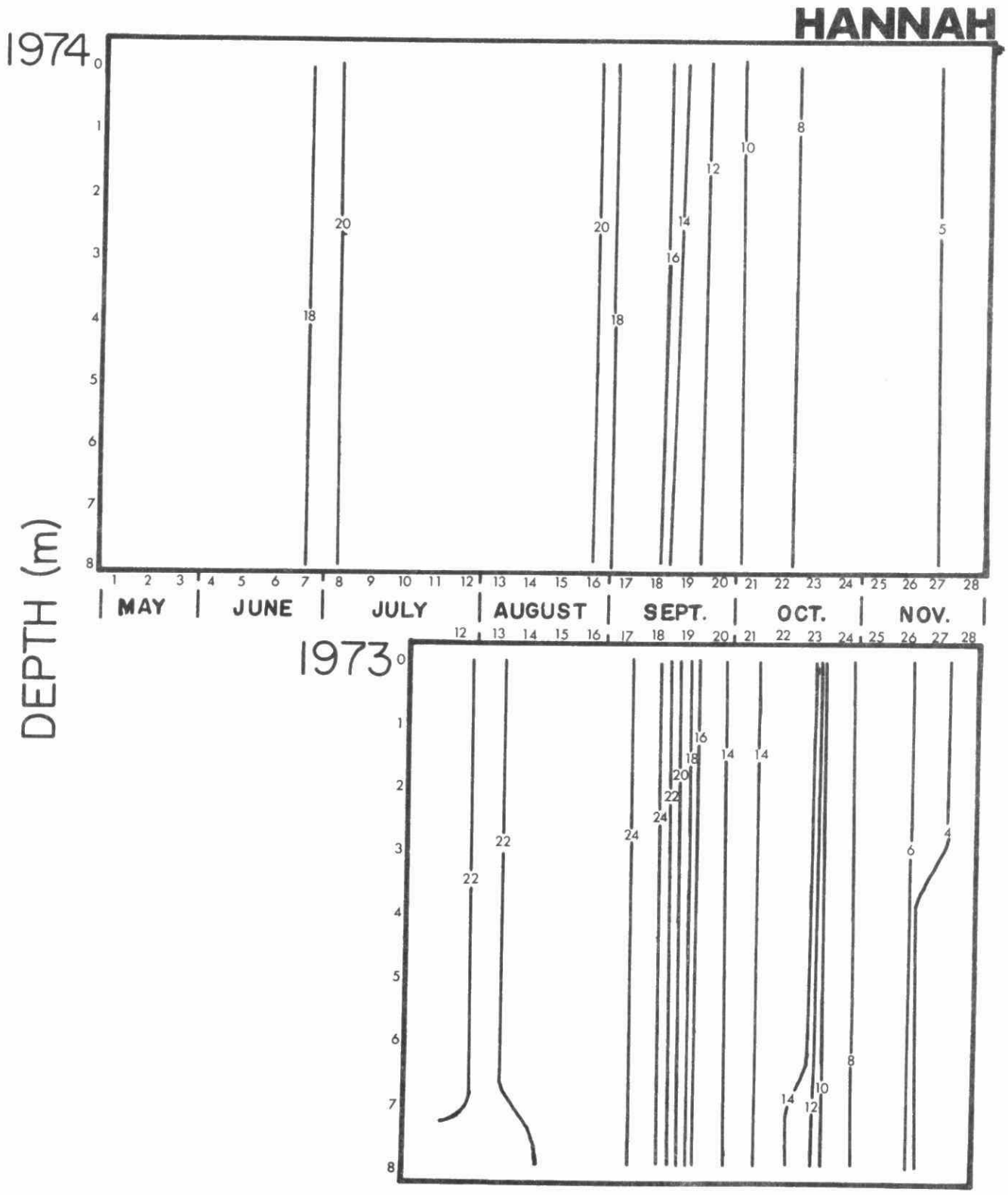
The four lakes exhibited a uniform drop in Secchi disc depths in 1974. This may be due in part to the increase in phytoplankton standing stock observed in all lakes. Middle Lake showed the greatest decline with mean summer values dropping from 11m in 1973 to 3m in 1974. Middle Lake also exhibited a blue-green colouration and turbid waters visually resembling the very hard waters of limestone quarries, chalk pits or marl lakes (Hutchinson 1957, Ruttner 1963). However, analysis showed that the water had low calcium content (14 ppm), moderate specific conductance (127 μmohs cm^{-1}) and a near neutral pH. Typical marl lakes have calcium of 50-90 ppm, specific conductances of 300-600 μmohs cm^{-1} and alkaline water with pH >8.0. The lack of these phenomena in Lohi Lake is added evidence that hydroxide was not the cause of the problem.

X-ray fluorescence analysis carried out on centrifuged (12,000 rpm) Middle Lake water showed the existence of a small amount of material high in silica, titanium and calcium with smaller amounts of iron and phosphorus. The calcium was not present as CaCO, $Ca(OH)_2$ or $CaCO_3$ and the compound was probably a clay type material (Dr. J.A. Pimenta, Air Quality Lab, pers. comm.). Soil erosion resulting

Figure 5: Isotherms for Reclamation Lakes 1973/1974.



TEMPERATURE (°C)



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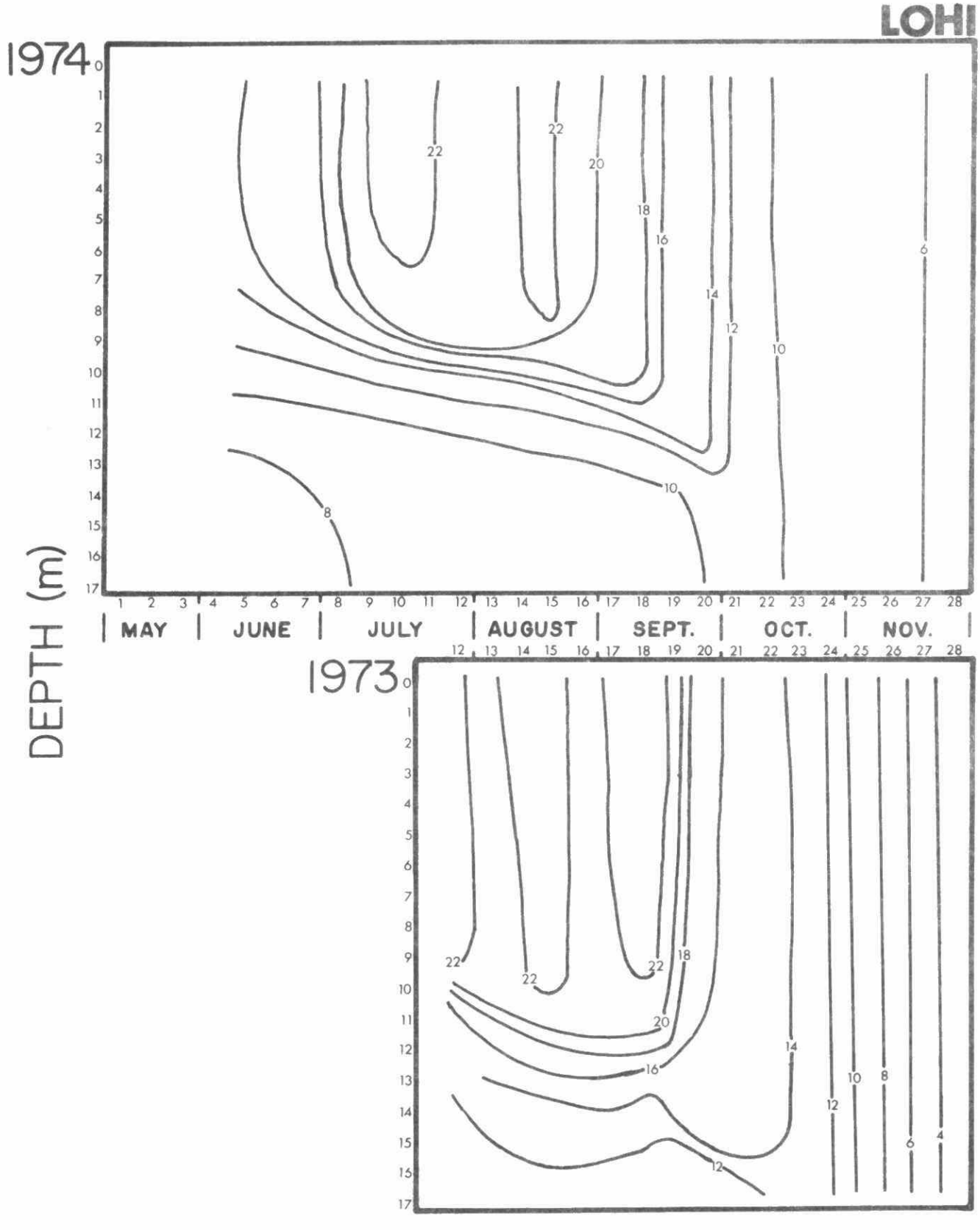
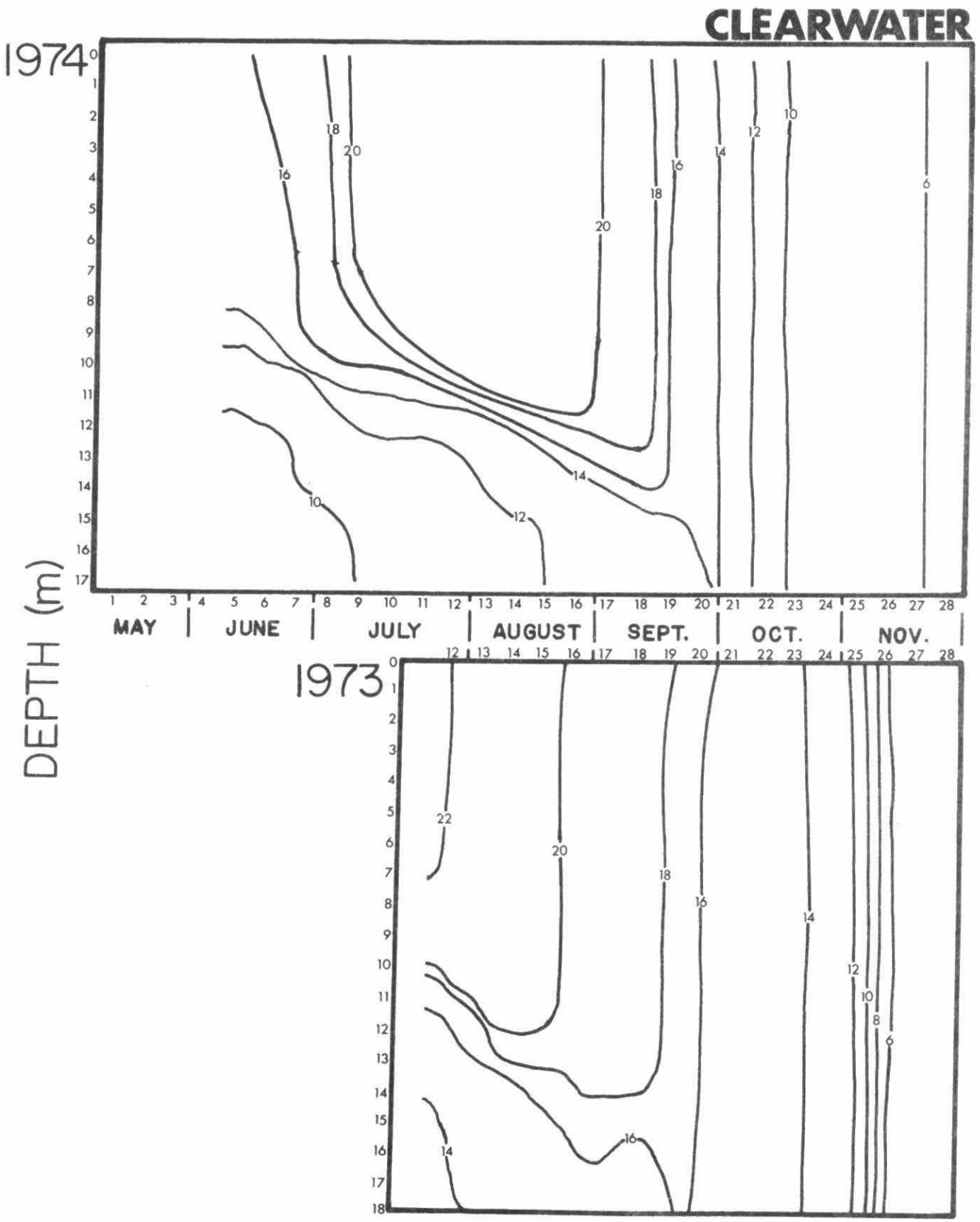


TEMPERATURE (°C)



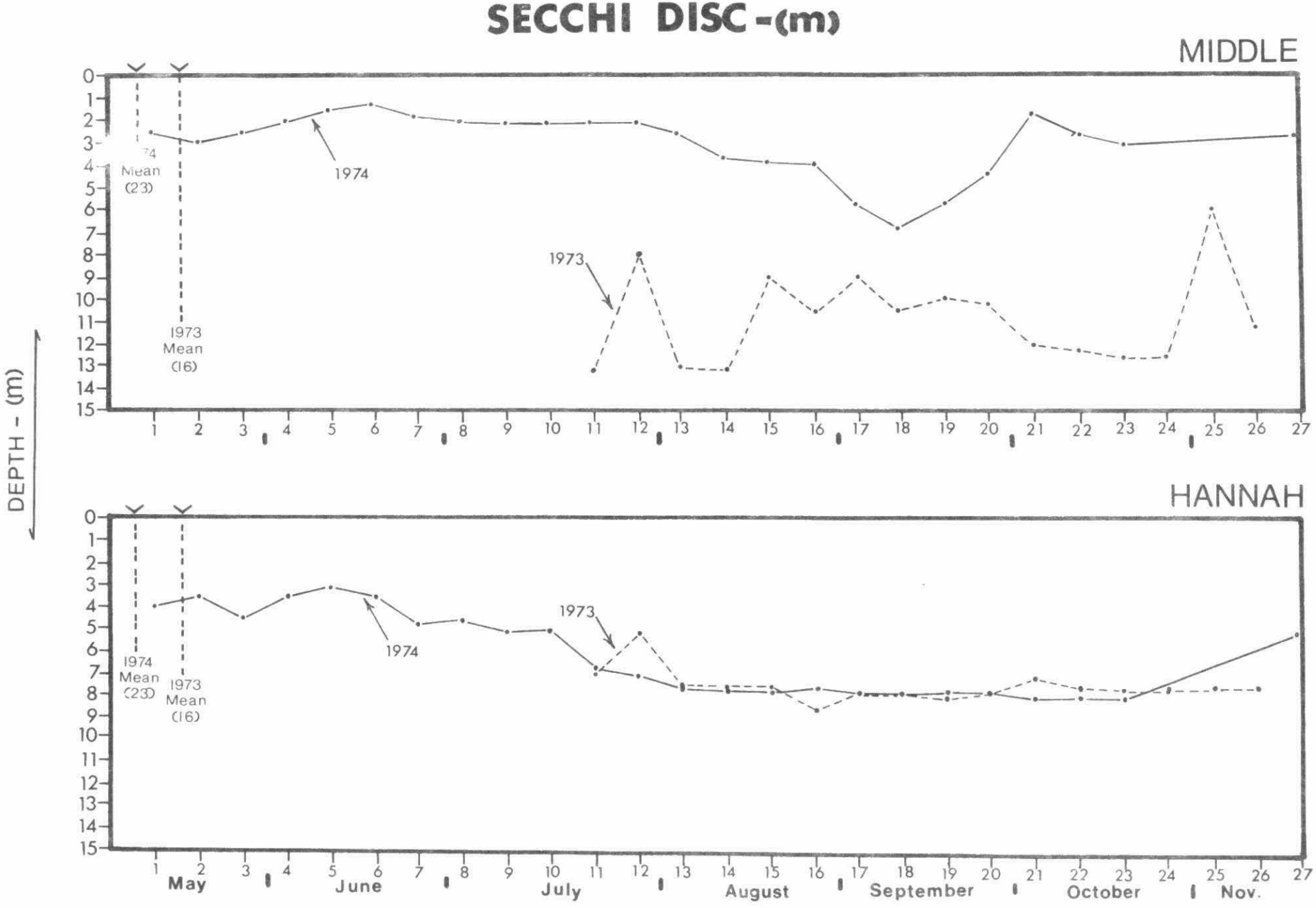
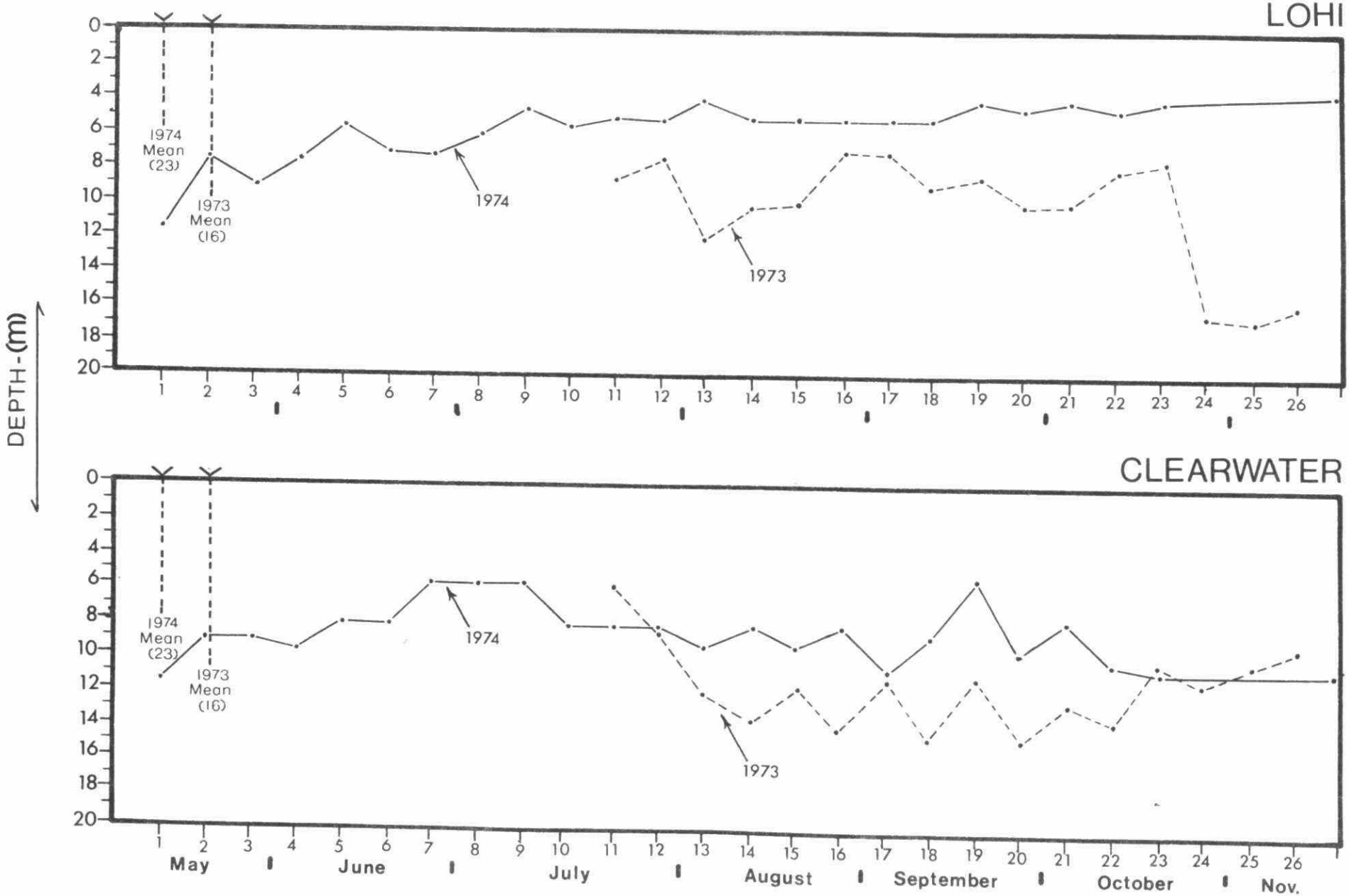


Figure 6: Secchi Disc Transparencies for Reclamation Lakes 1973/1974.

(Numbers, refer to week of sampling, dated from May 15, 1974 equals week #1)
>Mean is average of sampling season -(n) is number of samples.

SECCHI DISC - (m)



(Numbers refer to week of sampling dated from May 15th 1974 equals week 1)
Mean is average of sampling season - (n) is number of samples.

from the highway construction on the shores of Middle Lake is the probable source of the clay.

c) Dissolved Oxygen

All lakes were well oxygenated in both 1973 and 1974 with bottom water oxygen levels remaining above 6 ppm even at the height of summer stratification. The single exception to this is Lohi Lake which exhibited oxygen levels of less than 2 ppm below 15 m during the period of mid-August to the end of September 1973. The clinograde curve exhibited during this period is usually attributed to the decomposition of organic matter (Hutchinson 1957) but is not readily explained in this case. Limnetic plankton levels were low and sediment bacterial populations did not show a concurrent increase. At other times Lohi Lake oxygen curves were basically uniform with depth (orthograde) with a metalimnetic maximum in $[O_2]$ occurring in August 1974.

Clearwater showed basically orthograde oxygen curves in both 1973 and 1974 with slight metalimnetic maxima occurring in August. Middle Lake showed the same pattern as Clearwater in 1974, but because it was thermally homogenous in 1973, exhibited no metalimnetic maxima that year. Orthograde oxygen curves were found in Hannah Lake in 1973 and 1974 at all times because of its thermal homogeneity. Isopleths shown in Figure 7 show that liming had no apparent effect on the oxygen regimes of the lakes.

The orthograde curves exhibited are indicative of the low productivity of the lakes. The August metalimnetic maxima in oxygen concentrations (positive heterograde curve) may be due to localized phytoplankton activity (Hutchinson 1957). Phytoplankton often accumulate at this level because the increased water density slows their sinking.

2. Chemical Parameters

a) Water Chemistry

i) Major Ions

Pre-treatment chemical analyses show the four lakes to be soft (hardness 21 - 46 mg l^{-1}), poorly buffered (alkalinities 0.4 - 2.6 mg l^{-1}), with unusually low pH values (4.4 - 4.5). The dominant single ionic constituent was the sulphate ion (26 - 55 mg l^{-1}). Major cations associated with the

Figure 7a: Dissolved oxygen isopleths for Middle Lake.

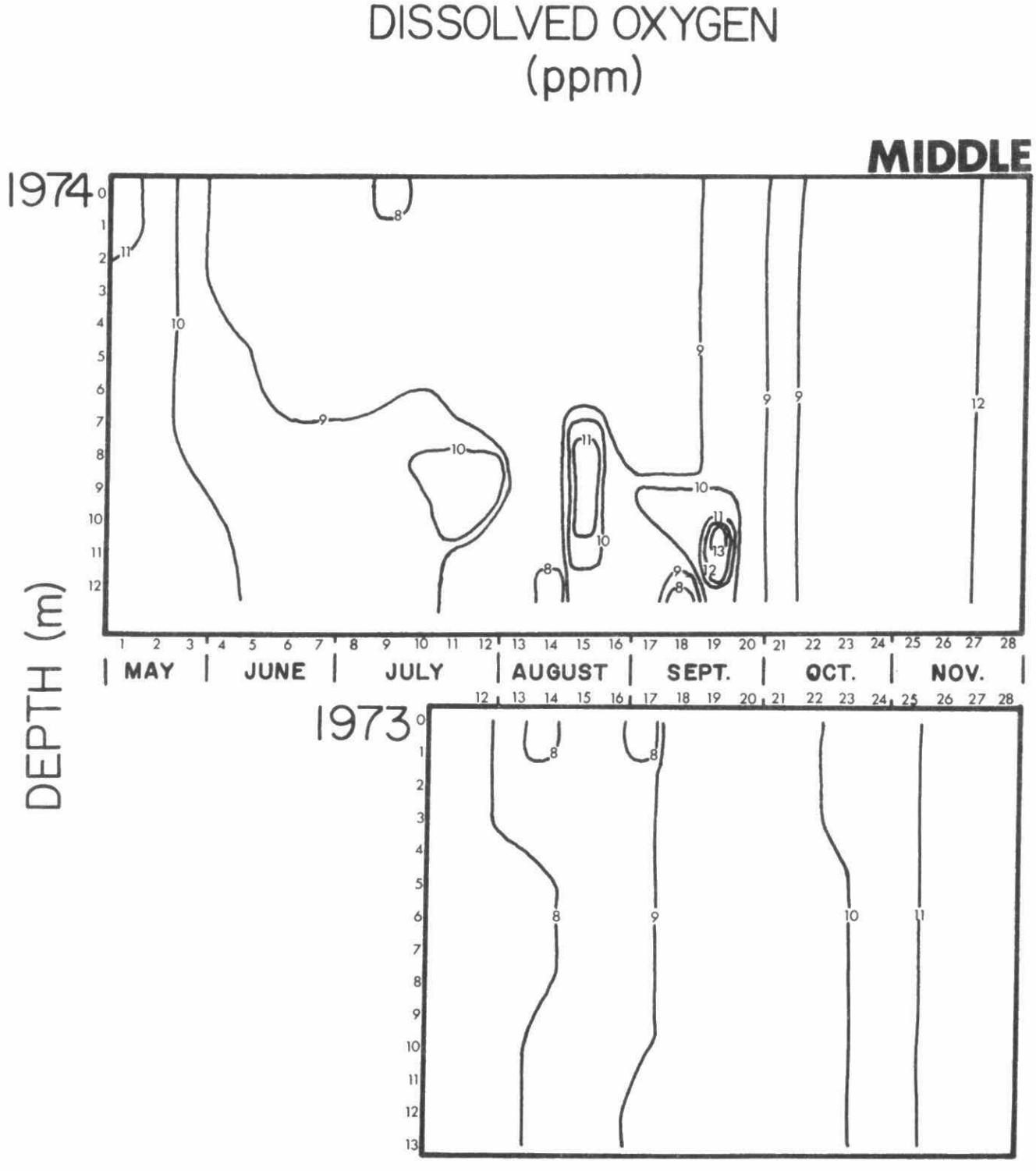


Figure 7b: Dissolved oxygen isopleths for Hannah Lake.

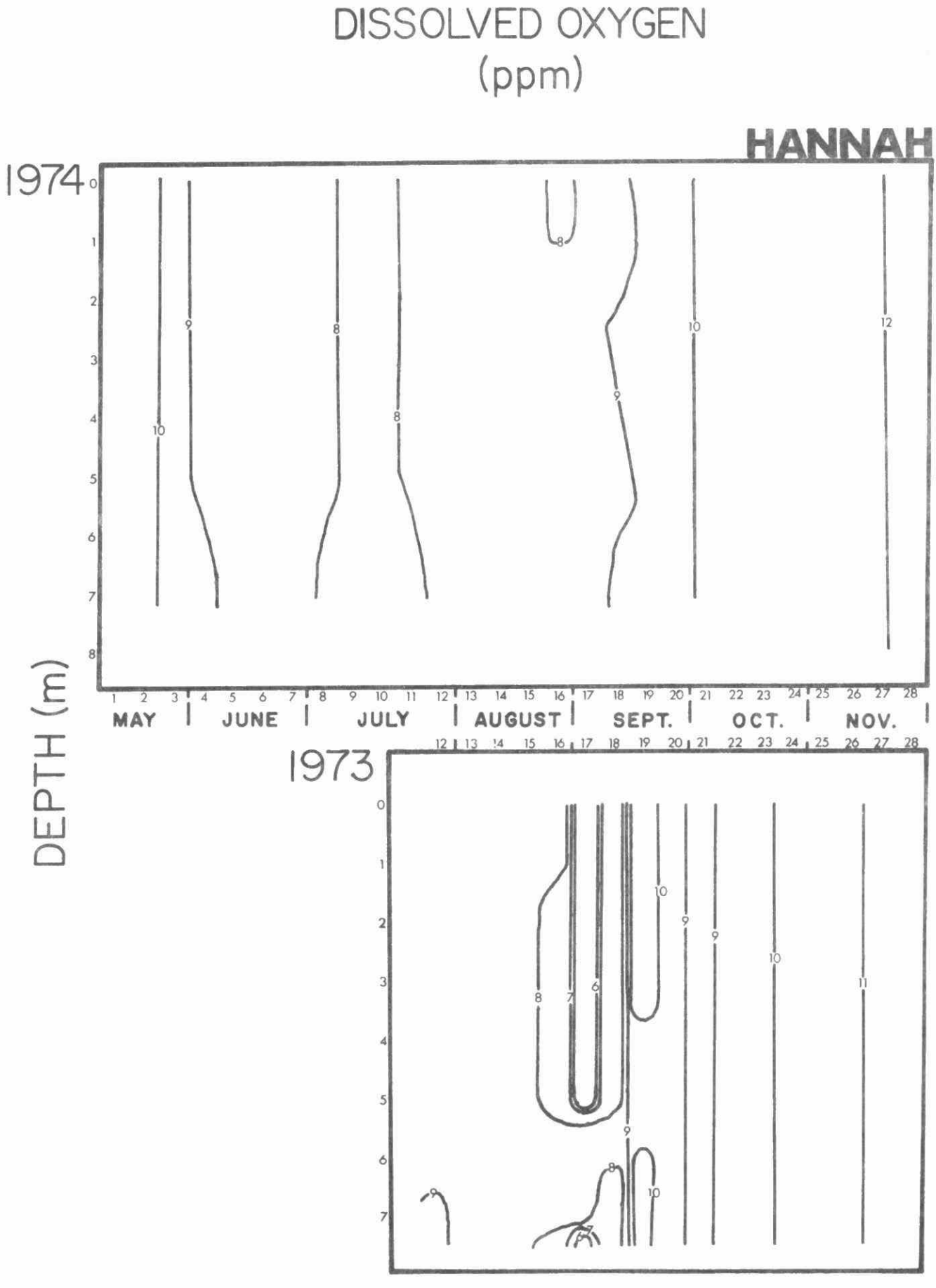


Figure 7c: Dissolved oxygen isopleths for Lohi Lake.

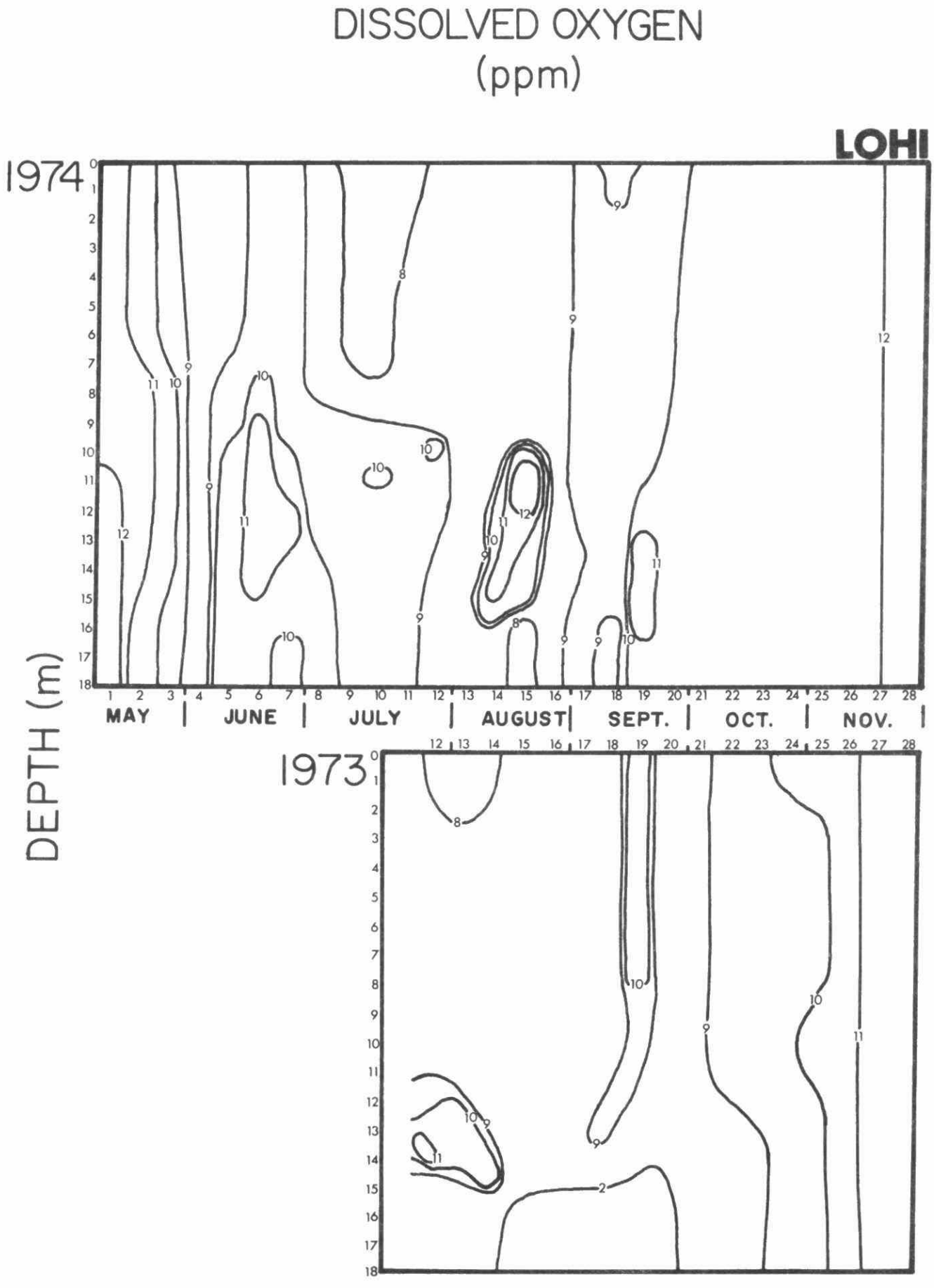
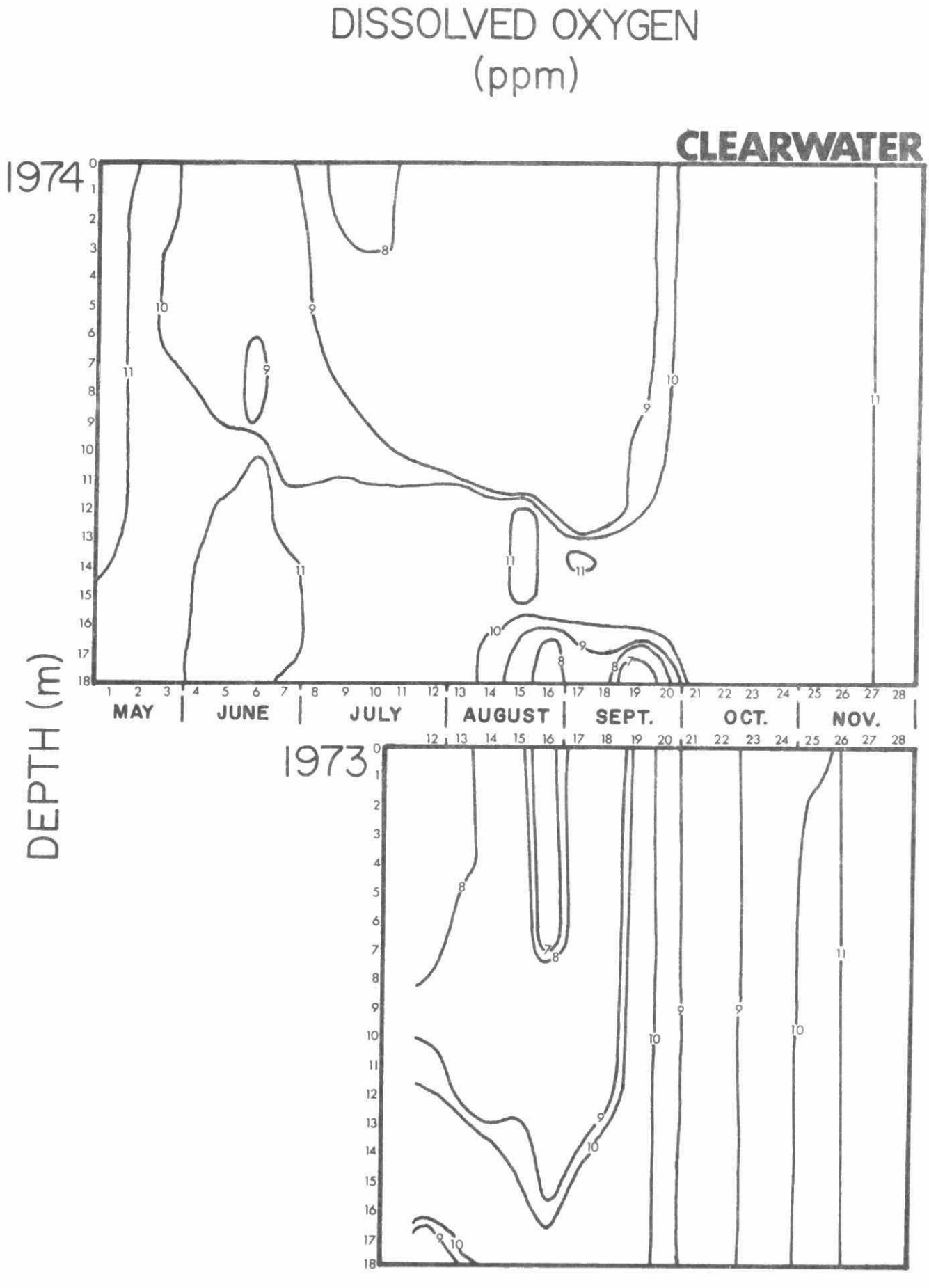


Figure 7d: Dissolved oxygen isopleths for Clearwater Lake.



sulphate were calcium (6.0 - 13.7 mg l^{-1}), magnesium (2.3 - 5.7 mg l^{-1}) with a small amount of hydrogen ion as well. Surface and bottom water chemistry was similar within the lakes. Appendix D summarizes the water chemistry.

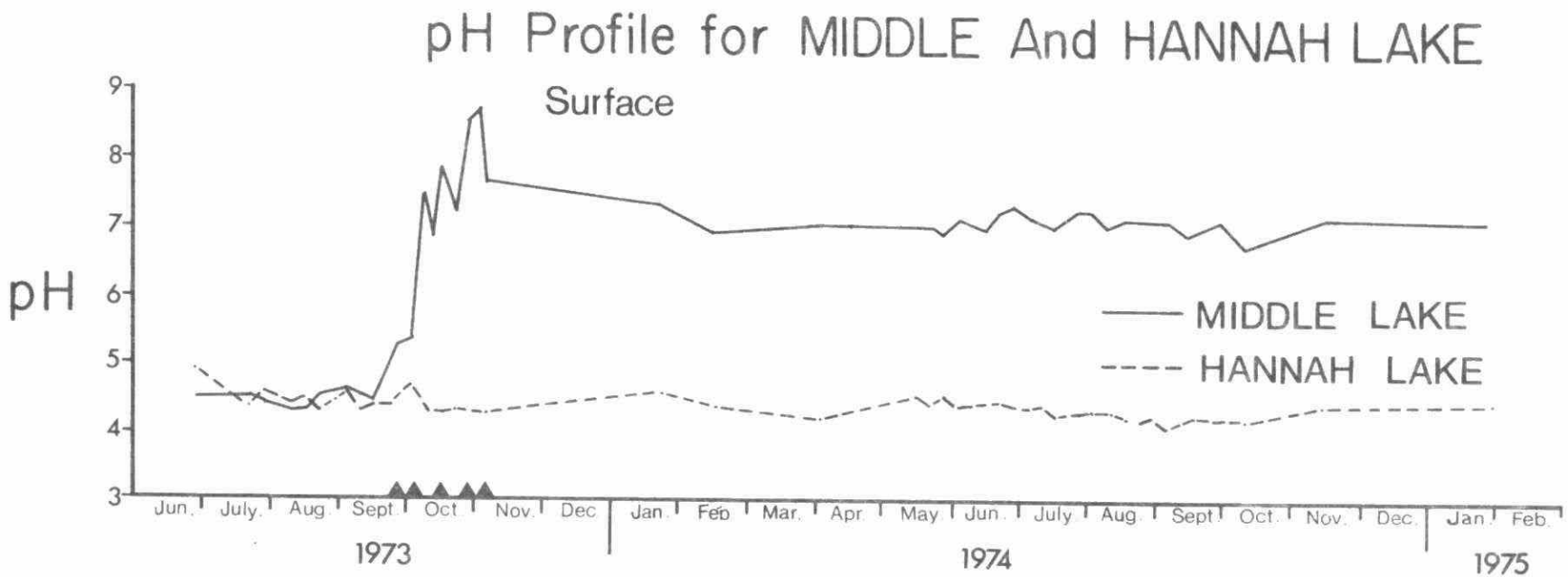
Armstrong and Schindler (1971) in reviewing the chemical characteristics of 23 lake areas on Canadian Shield bedrock found the major cationic species to be calcium (1.1 - 23.3 mg l^{-1}), magnesium (0.3 - 3.9 mg l^{-1}) and sodium (0.4 - 5.8 mg l^{-1}). The major anion present was usually bicarbonate (0.0 - 52.9 mg l^{-1} as $CaCO_3$) with sulphate concentrations well below values for the four experimental Sudbury lakes (0.0 - 10.3 mg l^{-1}). The pH range recorded was 4.7 to 8.7 with most lakes between 6.0 and 8.0.

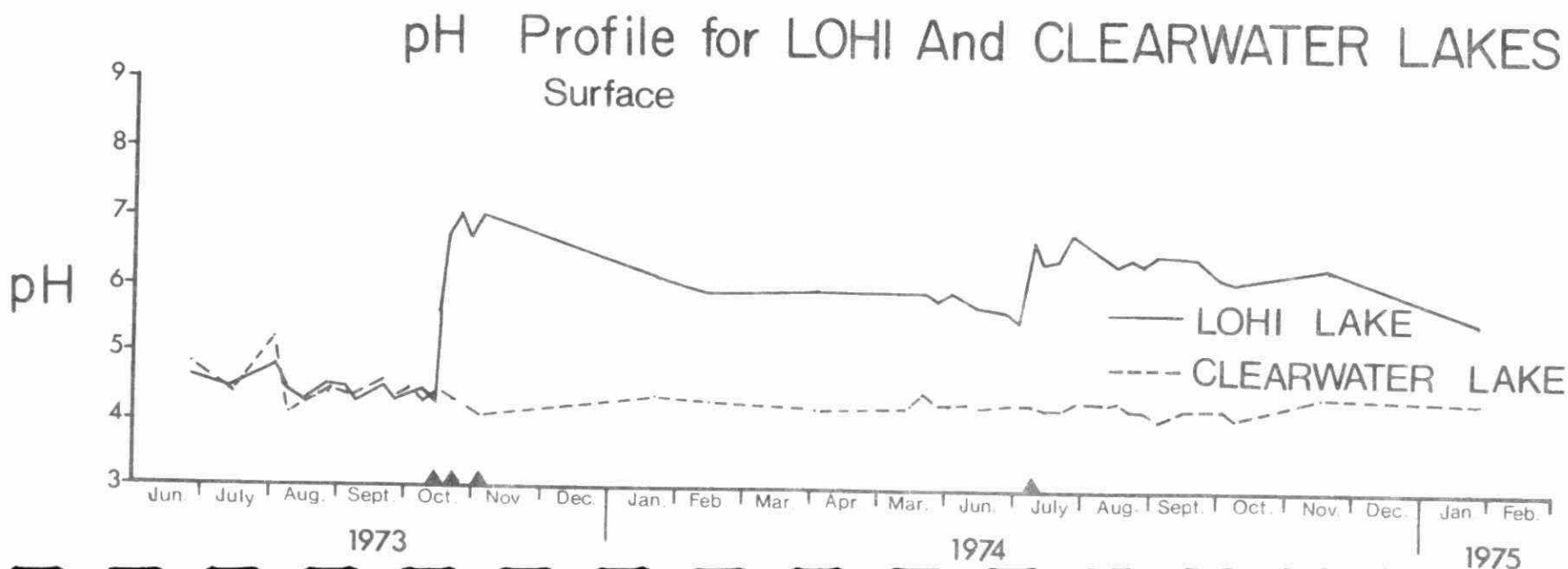
The atypical mineral balance of the Sudbury lakes is believed to be due to an artificial input of sulphate and hydrogen ions from industrial operations. This, combined with the naturally low calcium content of the bedrock, eventually resulted in a bicarbonate ion depletion, loss of buffering capacity and a reduction in the pH of the lake water.

The addition of the $Ca(OH)_2$ (and $CaCO_3$ in Middle Lake) altered the mineral chemistry in two ways. Any accumulated acidity was immediately neutralized and the pH of the lakes rose to neutrality. The calcium levels increased slightly (9 - 14 mg l^{-1} in Middle, 6 - 8 mg l^{-1} in Lohi) as a direct result of addition. Surface water alkalinity increased in Middle Lake from 0.4 mg l^{-1} to 6.9 mg l^{-1} (1974 mean value) with bottom water levels following the same trend indicating the re-establishment of a weak buffer system. Bicarbonate levels (surface) in Lohi increased from 0.6 to 2.2 mg l^{-1} (1974 mean value) with no change occurring in bottom water levels. Middle Lake showed the greater increase because of direct calcium carbonate additions.

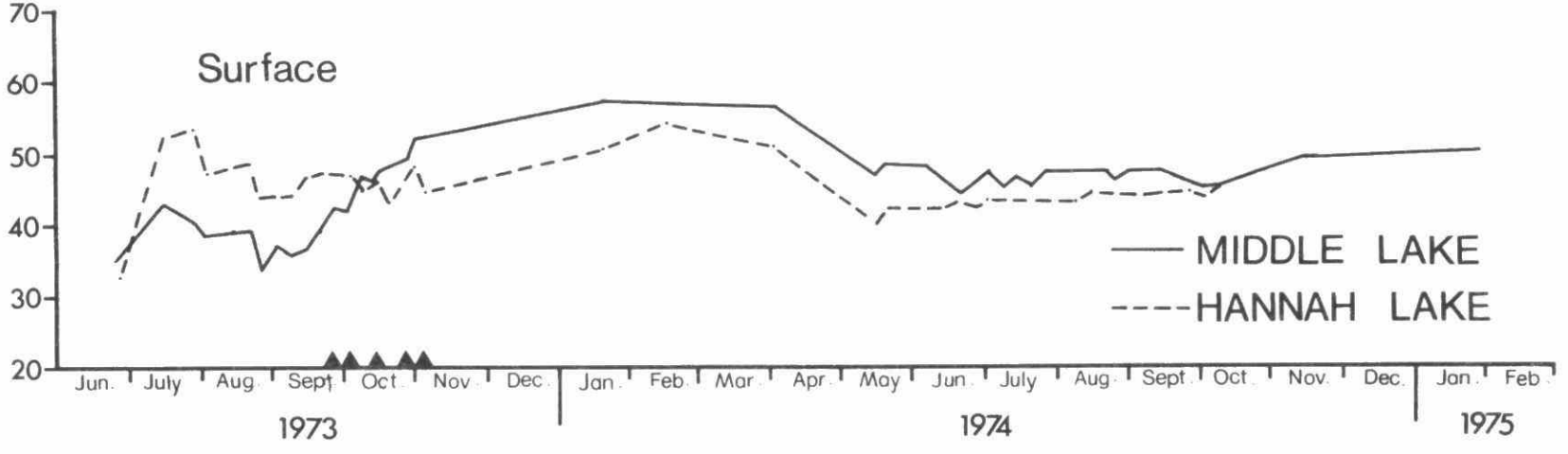
A concurrent increase in hardness followed treatment due to the addition of calcium. Specific conductivity decreased slightly as expected because of the hydrogen ion loss during neutralization. The input of calcium ions did not compensate for this loss. The concentration of these same parameters remained relatively constant over the two years in the two control lakes. Figures 8-11 outline the changes in pH, hardness, sulphate and specific conductance respectively for the four lakes with time.

Considerable seasonal fluctuations occurred in sulphate, hardness and specific conductivity in Middle and Hannah lakes with similar smaller fluctuations in Clearwater and Lohi. Values tended to be higher in the winter,

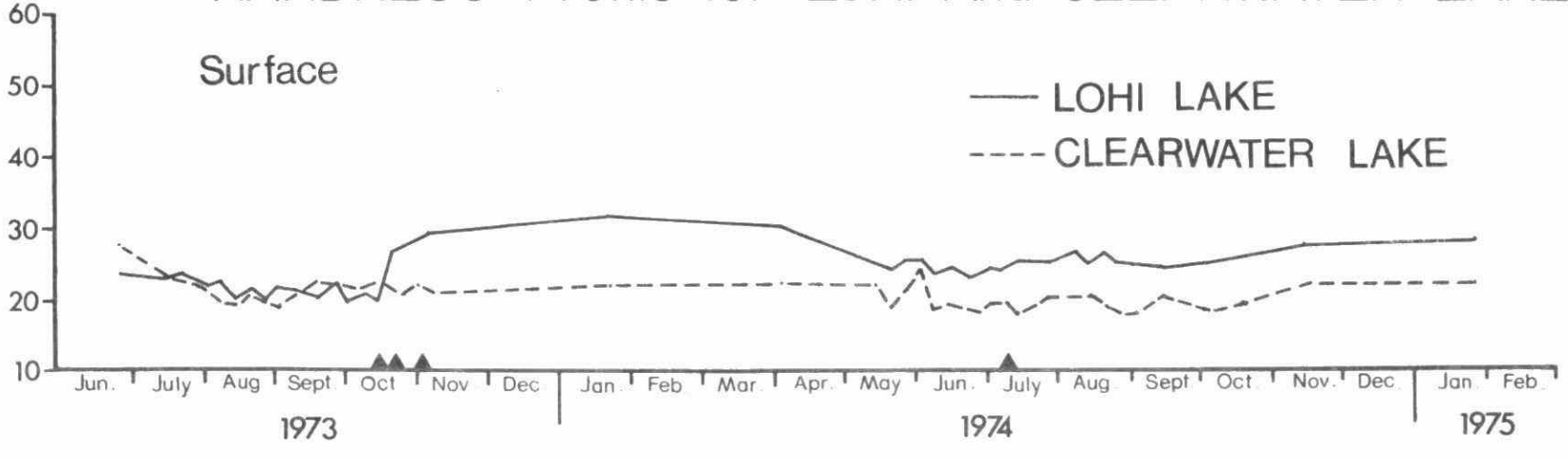

pH Profile for MIDDLE And HANNAH LAKE
Surface
pH
9
8
7
6
5
4
3
MIDDLE LAKE
HANNAH LAKE
Jun. July. Aug. Sept. Oct. Nov. Dec. Jan. Feb. Mar. Apr. May Jun. July Aug. Sept Oct. Nov. Dec. Jan. Feb.
1973
1974
1975

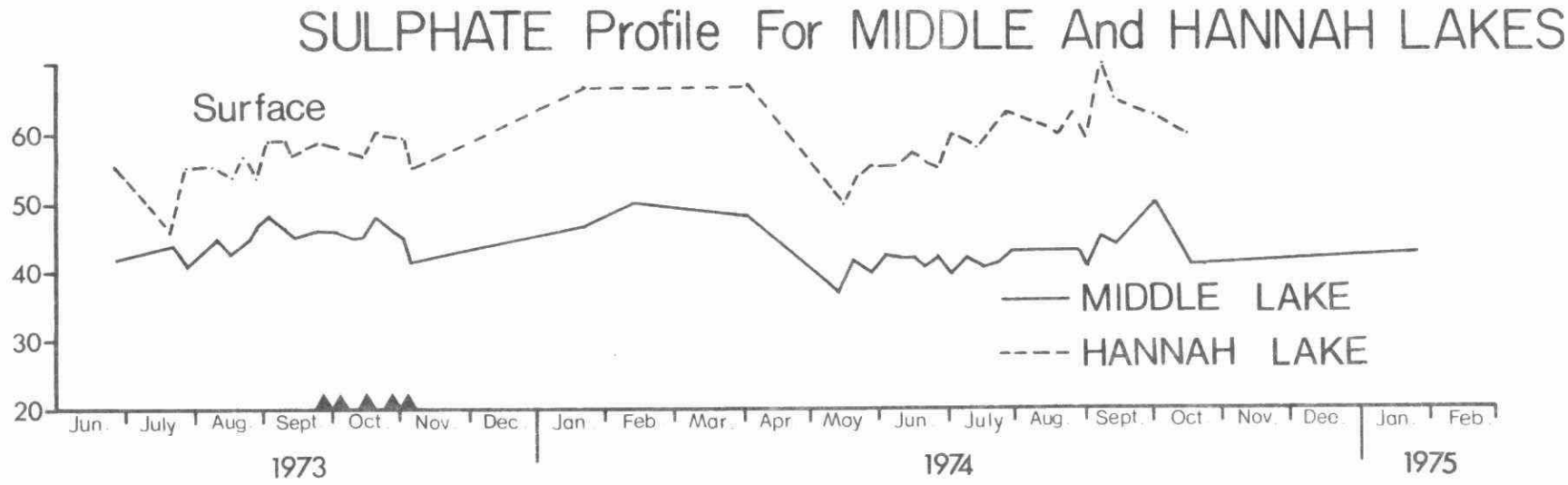

pH Profile for LOHI And CLEARWATER LAKES
Surface
pH
9
8
7
6
5
4
3
LOHI LAKE
CLEARWATER LAKE
Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb Mar. Apr. Mar. Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb.
1973
1974
1975

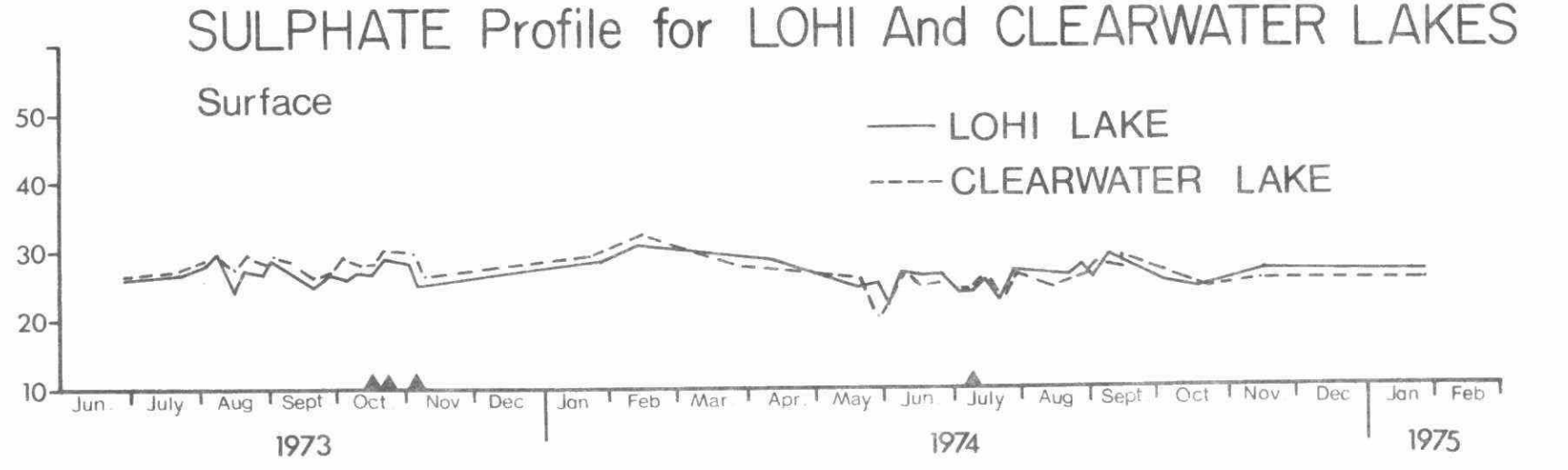
HARDNESS Profile for MIDDLE And HANNAH LAKES



HARDNESS Profile for LOHI And CLEARWATER LAKES




SULPHATE Profile For MIDDLE And HANNAH LAKES
Surface
60
50
40
30
20
MIDDLE LAKE
HANNAH LAKE
Jun
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Moy
Jun
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
1973
1974
1975


SULPHATE Profile for LOHI And CLEARWATER LAKES
Surface
50
40
30
20
10
LOHI LAKE
CLEARWATER LAKE
Jun
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
July
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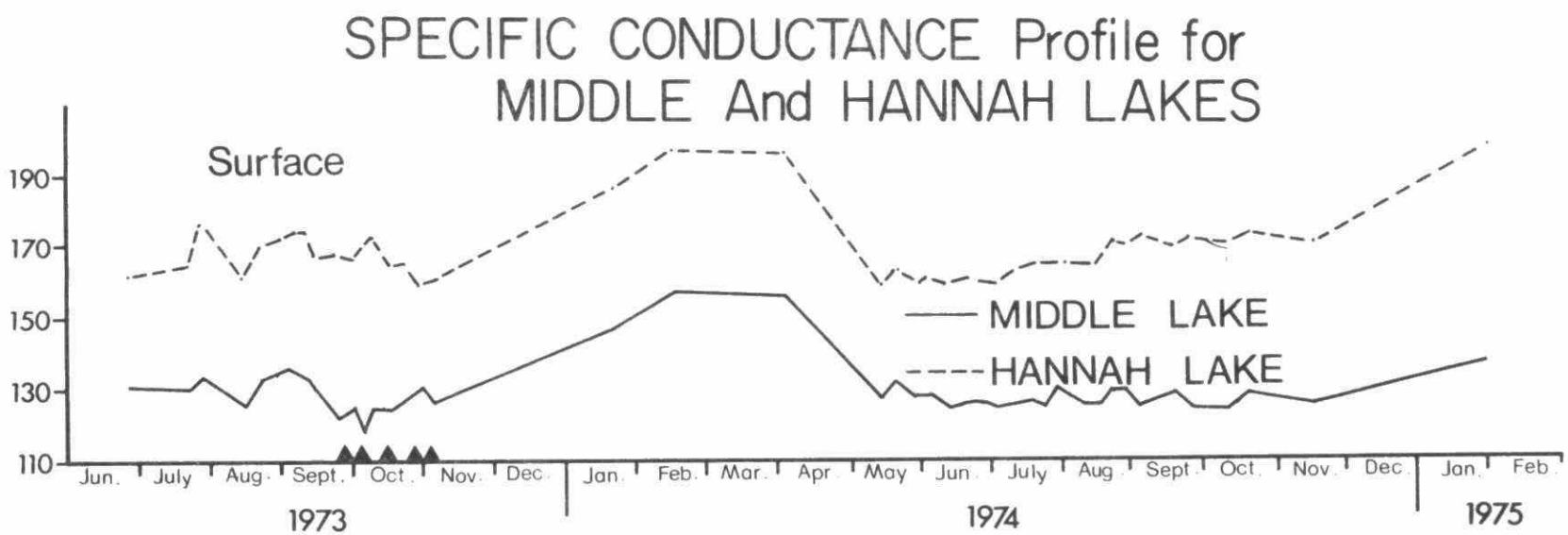
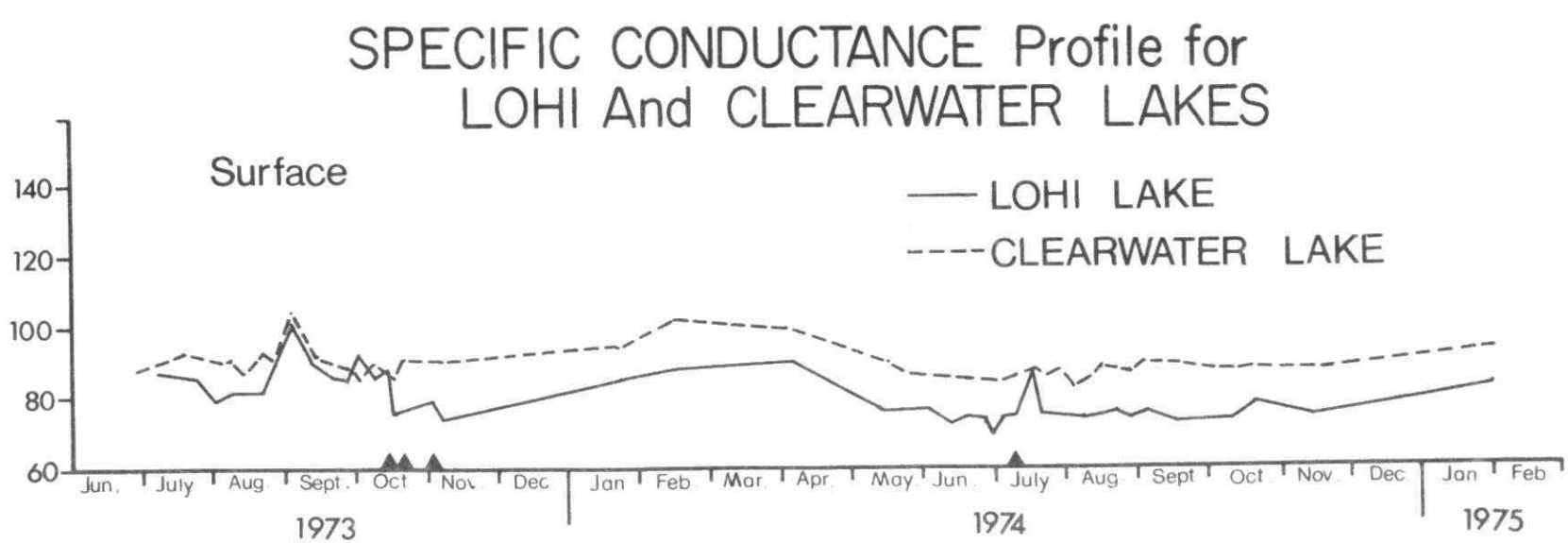
Oct
Nov
Dec
Jan
Feb
1973
1974
1975


SPECIFIC CONDUCTANCE Profile for
MIDDLE And HANNAH LAKES
Surface
190
170
150
130
110
MIDDLE LAKE
HANNAH LAKE
Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb. Mar. Apr. May Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb.
1973
1974
1975


SPECIFIC CONDUCTANCE Profile for
LOHI And CLEARWATER LAKES
Surface
140
120
100
80
60
LOHI LAKE
CLEARWATER LAKE
Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb. Mar. Apr. May Jun. July Aug. Sept. Oct. Nov. Dec. Jan. Feb.
1973
1974
1975

probably due to the greater solubility of $CaSO_4$ in cold water. The fact that the phenomenon is seen in both treated and control lakes eliminates the possibility of liming as the cause.

ii) Minor Ions

Most of the remainder of the mineral balance is made up of chloride, sodium, potassium and silicates. Calues reported for Shield Lakes (Armstrong and Schindler, 1971) show that the reclamation lakes fall within the typical ranges. Minor ion concentrations were similar for surface and bottom waters and did not vary with time in either the treated or control lakes.

iii) Heavy Metals

Background levels of heavy metals were high in all four lakes with the northern pair, Hannah - Middle, exhibiting higher concentrations than the Clearwater - Lohi system. Of major concern because of their toxicity to aquatic life are copper, with levels in the four lakes ranging from 0.19 mg l^{-1} to 1.12 mg l^{-1} (MBS) and nickel with a range of 0.28 mg l^{-1} to 1.85 mg l^{-1} (MBS). A comparison of surface and bottom data for control lakes in 1974 when a larger data base was available shows that concentrations were similar. Values quoted are for total metals. A single analysis done in May 1974 by anodic stripping voltammetry showed the free copper level to be 0.19 mg l^{-1} (17% of total copper) at the surface and 0.17 mg l^{-1} (15% of total) in the bottom waters of control Hannah Lake. Mount and Stephan (1969) point out that chronic long-term effects due to free copper ion toxicity can be expected between 10 and 20 µg l^{-1} in soft water. If we apply the ratio of free to total copper in Hannah Lake to the other lakes, it is evident that these toxic limits are exceeded in each case. Appendix E summarizes the heavy metal data.

Background data on 110 lakes in the Sudbury basin and surrounding area (OWRC, 1971) show a range of 0.0 to 0.76 mg l^{-1} in total copper levels and 0.0 to 2.05 mg l^{-1} in total nickel for lakes receiving no known direct industrial waste discharge. The four experimental lakes fall into the mid to upper levels of this range. The high heavy metal levels in the lakes are pr ly due to atmospheric input from local industrial operations as no direct mine tailing drainage enters them. A good correlation has been documented between lake water nickel levels and distance from the Sudbury smelting complex (OWRC, 1971). Data from the four lakes supports this finding

with heavy metal levels highest in the lakes closest to Sudbury.

Immediately after treatment, significant decreases occurred in the heavy metal levels of the bottom waters of the experimental lakes. Control lakes showed no similar decrease. Middle Lake showed reductions of 93%, 82%, 87% and 61% in copper, nickel, zinc and manganese respectively. Lohi Lake showed reductions of 86%, 52%, 73% and 25% in copper, nickel, zinc and manganese respectively. The increased concentration of these heavy metals in the sediment traps suggested a precipitation mechanism. Surface water heavy metal levels are lower in the treated than control lakes but the lack of pre-treatment baseline data precludes valid pre- and post-treatment comparisons. However, because 1974 data on control lakes showed the similarity of surface and bottom water levels, it may be assumed that the difference is due to the effects of liming.

Although short-term reductions in heavy metals were dramatic, levels slowly rose during 1974, especially in Lohi Lake. This is probably related to the gradual drop in pH although slight increases also occurred in neutral Middle Lake. Figures 12 and 13 show the change in the nickel and copper levels with time. Free copper determinations carried out in May 1974 indicate that levels may be toxic but the lack of data makes interpretation tenuous.

iv) Nutrients

For the purposes of the discussion, nutrients are defined as phosphorus, nitrogen and carbon. Mean values are summarized in Tables 10 and 11. . Pre-treatment total phosphorus levels were low, ranging from 5 to 8 $\mu g\ l^{-1}$. Because these values are so close to the detection limit of the analytical method (5 $\mu g\ l^{-1}$), absolute reliance must not be placed upon them. Total phosphorus ranges reported for "typical" Shield lakes in Ontario are 4.3 to 10.5 $\mu g\ l^{-1}$ (nine lakes studied by Dillon and Rigler, 1974a) and 6.9 to 12.1 $\mu g\ l^{-1}$ (six lakes studied by Scheider and Rigler, 1974). Conroy et al (1974) report levels of 0.5 - 29 $\mu g\ l^{-1}$ total phosphorus for 50 lakes in the Sudbury region. Armstrong and Schindler (1971) report a range of 3 - 20 $\mu g\ l^{-1}$ total dissolved phosphorus for 40 Shield lakes. The four experimental lakes lie at the lower end of these ranges, which themselves reflect the naturally nutrient-poor nature of Shield lakes.

Liming decreased the total phosphorus levels marginally, but interpretation is difficult due to levels near limits of analytical detection. Calcium hydroxide is commonly used in sewage treatment lagoons to precipitate phos

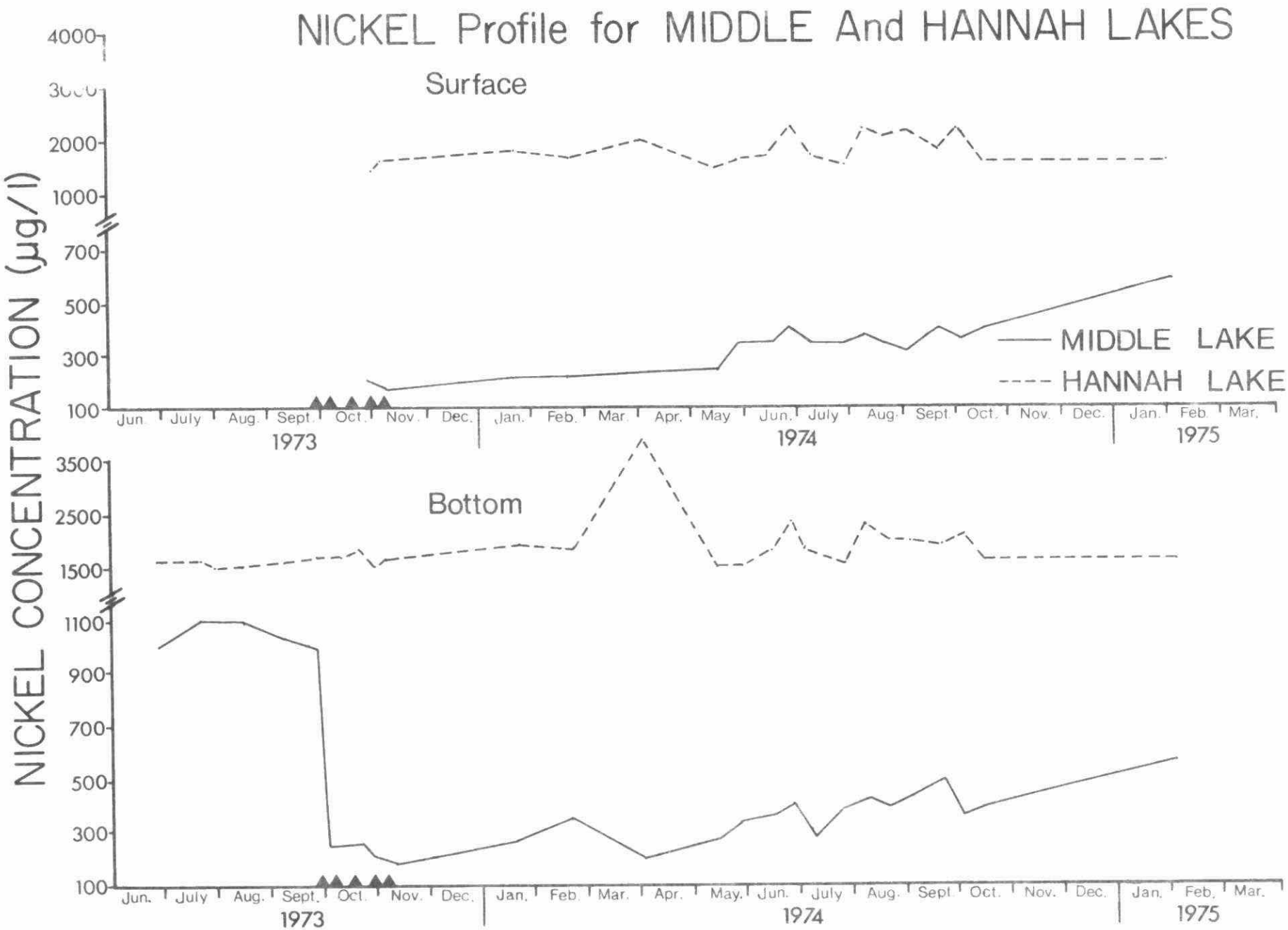


Figure 12a: Nickel Profiles for Middle and Hannah Lakes.

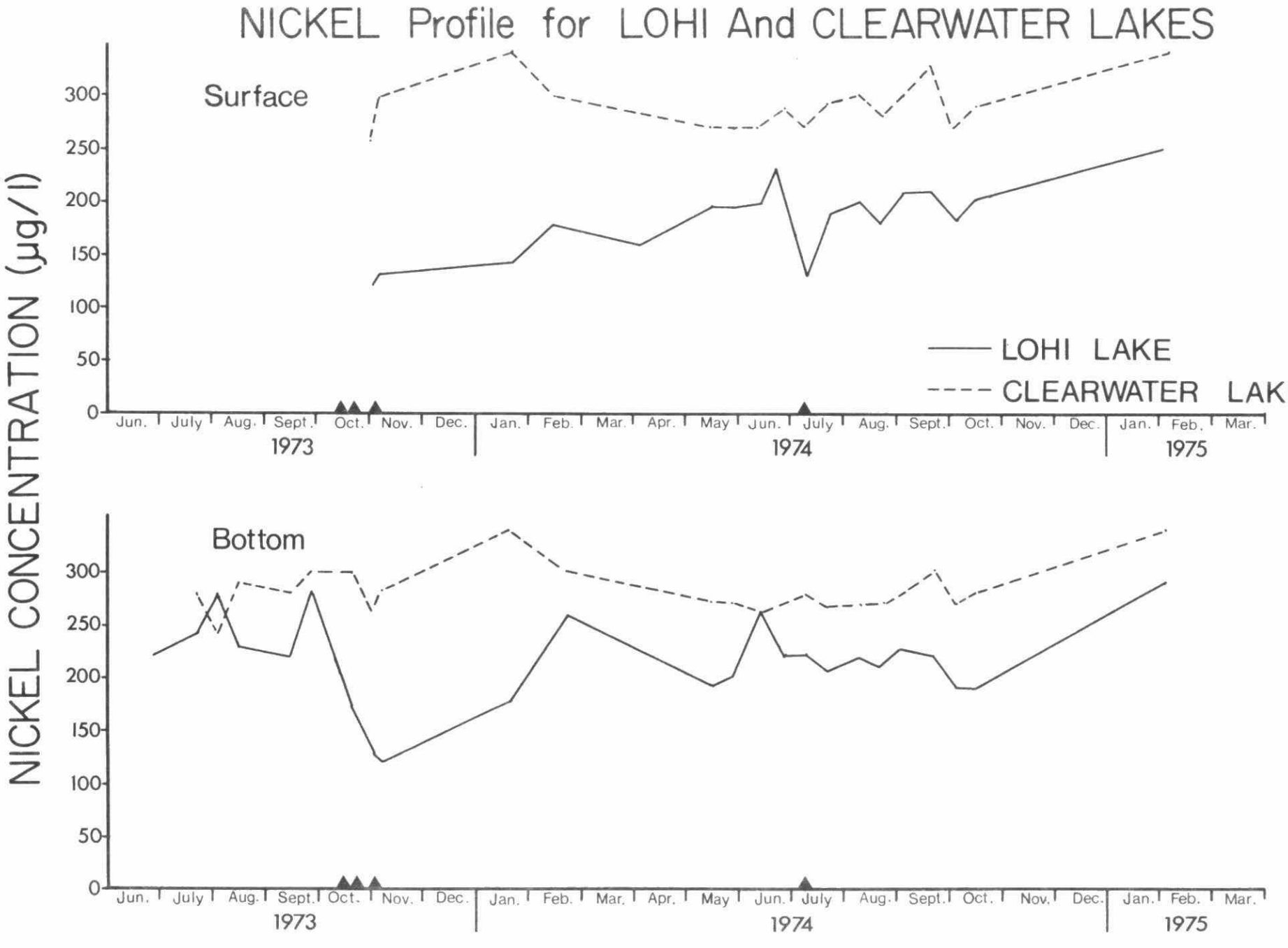


Figure 12b: Nickel Profiles for Lohi and Clearwater Lakes.

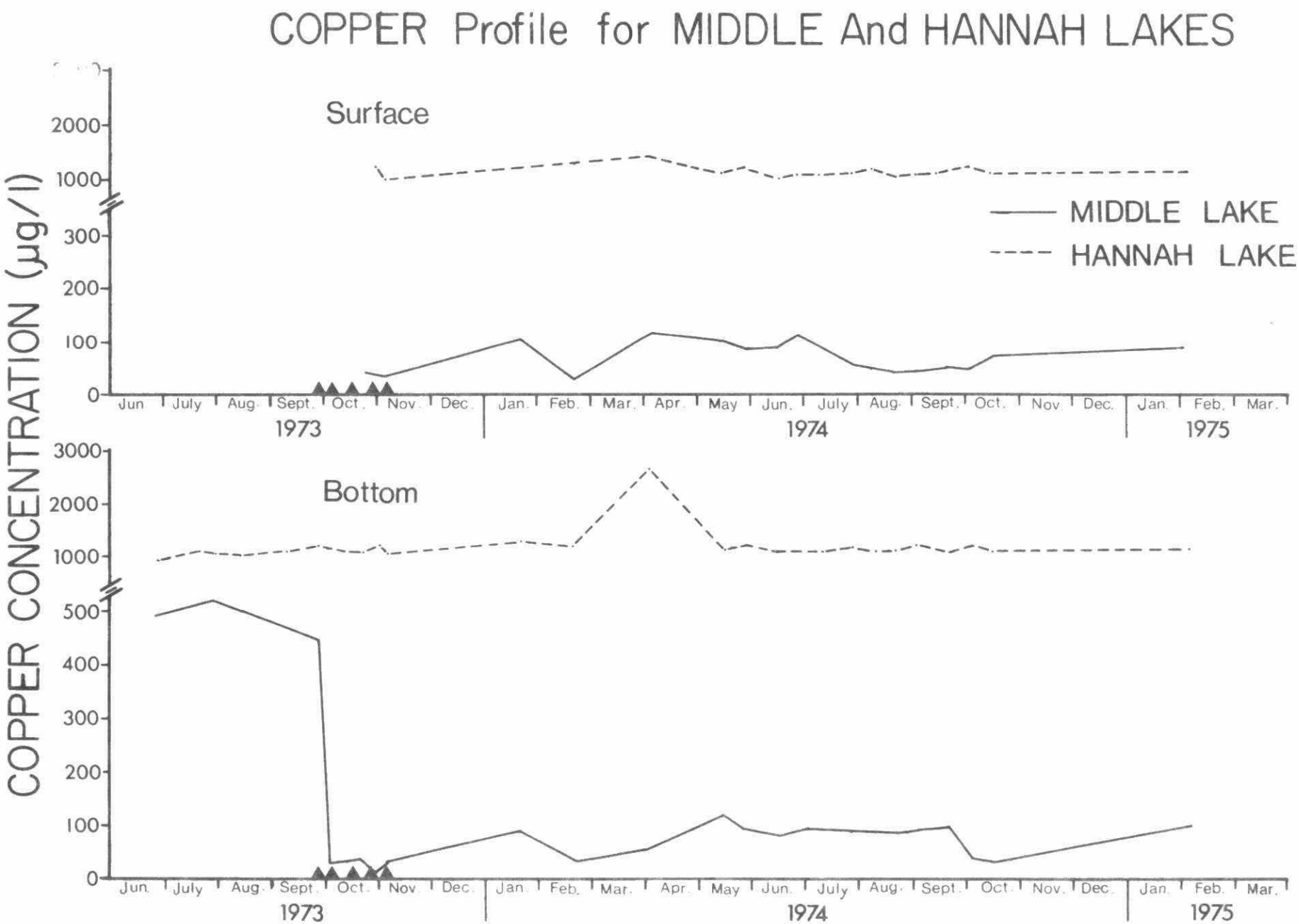


Figure 13a: Copper Profiles for Middle and Hannah Lakes

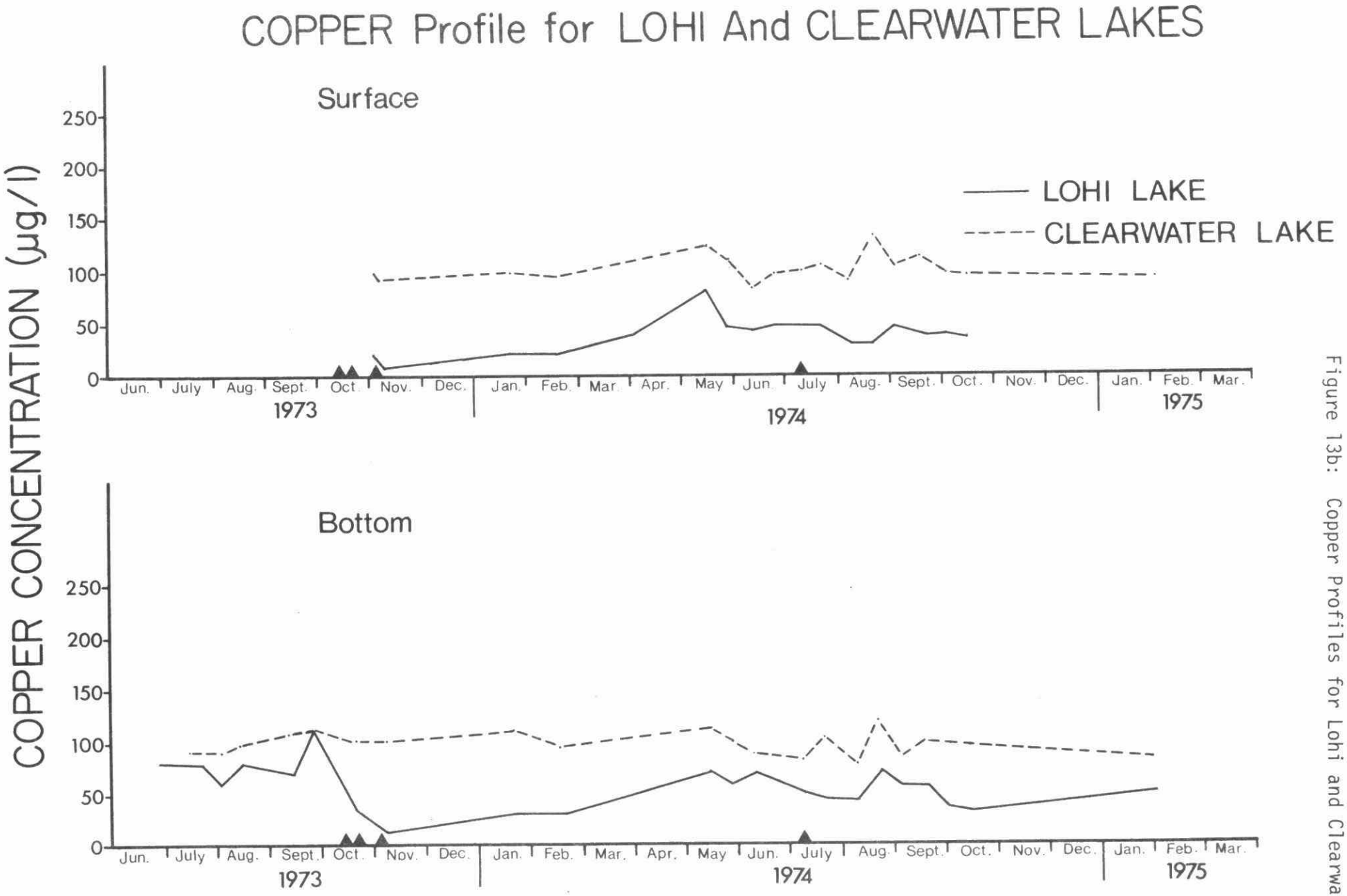


Figure 13b: Copper Profiles for Lohi and Clearwater Lakes.

Table 10 : 1973/1974 Phosphorus and Nitrogen (mg l^{-1})

Hannah Lake

		Parameter					
		NH_3	Kj.N	NO_3	NO_2	Total N	Total P
1973 Preliming	$\bar{x}$	.11	.24	.68	.001	.93	.008
	N	10	10	10	10	10	10
	S	.12	.12	.13	.001	.20	.002
1974	$\bar{x}$	.02	.15	.55	.001	.70	.005
	N	20	22	23	19	23	18
	S	.02	.07	.15	.001	.17	.003

Middle Lake

1973 Preliming	$\bar{x}$	.04	.18	.40	.001	.58	.007
	N	10	10	10	8	10	10
	S	.02	.05	.15	.001	.17	.004
1973 Postliming	$\bar{x}$	.02	.17	.40	.003	.57	.006
	N	6	6	6	6	6	4
	S	.01	.07	.05	.003	.10	.002
1974	$\bar{x}$	.05	.18	.46	.006	.57	.006
	N	22	23	22	23	23	21
	S	.02	.03	.12	.001	.15	.004

$\bar{x}$ = mean

S = standard deviation

Table 10 : Continued

		NH_3	Kj.N	NO_3	NO_2	Total N	Total P
Clearwater Lake							
1973 Preliming	$\bar{x}$	.04	.12	.32	.001	.44	.005
	N	11	12	12	10	12	11
	S	.03	.05	.72	.001	.06	.001
1974	$\bar{x}$	.02	.08	.06	.001	.15	.005
	N	18	22	19	15	22	21
	S	.01	.02	.02	.001	.03	.003
Lohi Lake							
1973 Preliming	$\bar{x}$	.07	.20	.08	.001	.28	.006
	N	12	11	12	10	11	11
	S	.03	.07	.04	.001	.05	.004
1974	$\bar{x}$	.02	.11	.08	.001	.19	.005
	N	12	23	22	23	22	19
	S	.01	.03	.02	.001	.03	.003

$\bar{x}$ = mean

S = standard deviation

Table 11 : 1973/1974 Carbon (mg l^{-1})

Hannah Lake

		Parameter				
		MBS CO_2	MAB CO_2	Composite Inorganic C	Composite Organic C	Composite Total C
1973 Preliming	$\bar{x}$	10.9	10.9	.66	5.85	6.12
	N	7	7	9	8	8
	S	.7	.7	.11	2.08	2.19
1973 Postliming	$\bar{x}$	12.0	12.0	.95	6.40	7.49
	N	4	3	6	5	5
	S		1.0	.52	2.61	2.46
1974	$\bar{x}$	11.0	11.3	.72	2.12	2.76
	N	23	23	16	16	16
	S	.6	.5	.32	.66	.60

Middle Lake

1973 Preliming	$\bar{x}$	8.3	7.7	.89	5.50	6.75
	N	6	6	9	8	8
	S	.4	.8	.18	2.15	1.87
1973 Postliming	$\bar{x}$	3.3	3.0	1.34	7.20	8.25
	N	3	3	6	5	5
	S	.3		.45	2.82	2.66
1974	$\bar{x}$	1.3	3.6	2.06	2.44	4.57
	N	23	22	14	14	13
	S	.4	1.7	.32	.79	.81

$\bar{x}$ = mean

S = standard deviation

Table 11: continued.

Clearwater Lake

		MBS CO_2	MAB CO_2	Composite Inorganic C	Composite Organic C	Composite Total C
1973 Preliming	$\bar{x}$	6.2	6.1	.82	6.04	7.51
	N	10	10	12	11	11
	S	.4	.6	.24	2.49	3.11
1973 Postliming	$\bar{x}$	-	-	.73	4.75	5.40
	N	-	-	3	2	2
	S	-	-	.13	.25	.05
1974	$\bar{x}$	6.7	7.7	.75	1.90	2.56
	N	23	22	16	16	16
	S	.5	1.3	.27	.92	.77

Lohi Lake

1973 Preliming	$\bar{x}$	5.8	14.5	1.25	7.04	8.32
	N	10	10	12	11	11
	S	8	7.3	.49	2.15	2.43
1973 Postliming	$\bar{x}$	.9	.9	.88	4.75	5.75
	N	1	1	3	2	2
	S	-	-	.09	.25	.05
1974	$\bar{x}$	1.6	4.1	.90	2.23	3.08
	N	23	21	17	16	16
	S	.7	1.8	.31	1.02	.96

$\bar{x}$ = mean

S = standard deviation

phorus as calcium phosphate but pH levels at which efficient removal occurs are in excess of 10.5 (Jenkins, Ferguson and Menar, 1971). However, calcium phosphate precipitation at pH 7.5 - 9.5 has been noted in waters of low alkalinity and magnesium content (Ferguson and McCarty, 1970, in Jenkins et al, 1971).

Nitrite and ammonia nitrogen levels were low, being near the detection limits of the methods employed. Kjeldahl nitrogen ranged from 0.12 to 0.24 mg l^{-1} and fell in the range of values reported by Armstrong and Schindler (1971) for 40 Shield lakes (0.10 - 0.30 mg l^{-1} total dissolved nitrogen). Nitrate composed the largest fraction of the total nitrogen in each lake. Concentrations (0.02 - 0.68 mg l^{-1}) fell at the lower end of the range reported in the literature (0.02 - 3.1 mg l^{-1}) as summarized in Armstrong and Schindler (1971).

Liming had no apparent effect on the inorganic nitrogen levels of the lakes. A slight decrease in Kjeldahl nitrogen occurred in Lohi Lake. Tests on the effects of lime on nitrogen levels in lagoons (Graham and Hunsinger, 1972) showed no appreciable effects on inorganic forms and a reduction in organic nitrogen, probably due to a precipitation phenomenon.

Carbon dioxide levels in the lakes compared well with the range (0.3 - 12.0 mg l^{-1}) reported by Armstrong and Schindler (1971). Total carbon values were low in the Sudbury lakes with organic carbon comprising the major fraction. Inorganic carbon levels were near the detection limit.

Liming decreased the CO_2 content of the lakes as would be expected. The higher pH would shift the CO_2-HCO_3^--CO_3^{2-} system to the right. Carbon levels generally declined in 1974 in both treated and control lakes.

b) Sediment Chemistry

A characterization of the sediment chemistry for the treated lakes is given in Table 12. Values for Harp Lake, an oligotrophic Shield lake in the Muskoka Lakes Area are included for comparative purposes. Caution must be used in the interpretation of the data as intralake variation in sediment composition was large. Brunskill, Povoledo, Graham and Stainton (1971) found that most parameters studied in the surface sediments of 16 Shield lakes with homogenous drainage areas varied by a factor of 3 - 5. Data for the four Sudbury lakes show intralake variations of up to a factor of 10. The pre-treatment sediment chemistry for the three lakes is similar with two notable

Table 12: Sediment Chemistry of Middle, Lohi and Harp Lakes.

Chemical Parameter	Section of Core	Middle Lake 1973	Middle Lake 1974	Lohi Lake 1973	Lohi Lake 1974	Harp Lake 1973 (Eckman Dredge)
% Loss on Ignition	Top	22	18	16	16	27
	Bottom	25	24	17	19	
Kjeldahl Nitrogen (mg/g)	Top	7.0	7.5	5.5	5.9	9.3
	Bottom	7.7	8.8	5.8	6.5	
Total Phosphorus (mg/g)	Top	1.3	1.2	1.1	0.95	2.3
	Bottom	1.4	1.5	1.2	1.1	
Copper (µg/g)	Top	1140	2060*	448	636	35.9
	Bottom	226	1090*	116	147	
Nickel (µg/g)	Top	1710	3010*	563	848*	<5.0
	Bottom	344	1497*	145	191	
Zinc (µg/g)	Top	145	188	127	107	153
	Bottom	130	147	107	102	
Iron (%)	Top	3.84	2.56	2.33	2.55	2.57
	Bottom	2.15	1.31*	2.00	1.71	
Manganese (µg/g)	Top	261	316	235	196	897
	Bottom	382	186*	329	251*	
Calcium (µg/g)	Top	2120	15700*	1720	1500*	5500
	Bottom	2230	16300	2570	1970*	
Magnesium (µg/g)	Top	3130	6021*	4120	2640*	3530
	Bottom	3190	4530	5130	2850*	
pH	Top	5.4	5.9*	5.4	6.2*	
	Bottom	6.2	5.5*	5.9	6.3	
Lime demand (g $Ca(OH)_2$/kg wet sediment)	Top	2.17	1.31*	1.54	.91*	
	Bottom	1.64	2.05*	1.28	1.06	

*indicates a statistically significant ($P < 0.05$) change using a two-tailed t test for data sets with non-equivalent variances.

exceptions. Copper and nickel levels are roughly three times higher in Middle than Lohi and both Sudbury lakes have levels of 1 - 3 orders of magnitude higher than Harp Lake. This coincides with the observation that the nickel concentrations in lake water decrease with distance from the smelting complex (OWRC 1971) and suggests a local source of emissions. It is also noteworthy that the sediments of the three lakes showed similar levels of zinc, a negligible component of smelter emissions.

Results of sediment profile analysis (taken 1974) are plotted in Figures 14 to 16. Patterns are complicated by intralake variation and the fact that sediment mixing can occur to 5 - 20 cm below the sediment surface (Lee, 1970). However, several general trends may be discerned. Copper and nickel levels are highest in Middle and Hannah lakes, with all lakes showing higher concentrations in the upper layers of the core. This is indicative of recent deposition but because sedimentation rates are not known, no time scale can be given. Sediment pH is similar at the 10 cm depth in all lakes and drops fairly regularly to 3.7 - 4.2 in the top 1 cm of the control lakes. Treated lakes do not follow this pattern and show pH values of 4.7 - 6.3 in the top 1 cm. Sadana (1974) gives a more complete discussion of the sediment profiles.

The effect of liming on the sediment chemistry is summarized in Table 12. Significant changes included an increase in pH, copper and nickel levels of the surface sediments, the latter presumably due to precipitation of lake water metals. To assess the extent of sediment neutralization, a lime demand parameter was calculated as the amount of $Ca(OH)_2$ necessary to titrate a sediment sample to a pH endpoint of 8.0. Approximately 40% of the pre-treatment lime demand was satisfied in both lakes. Assessment of sediment neutralization is complicated by microbiological activity which may act to neutralize or acidify the sediments depending upon which type of bacteria are present.

Figure 14:

Sediment pH Profiles

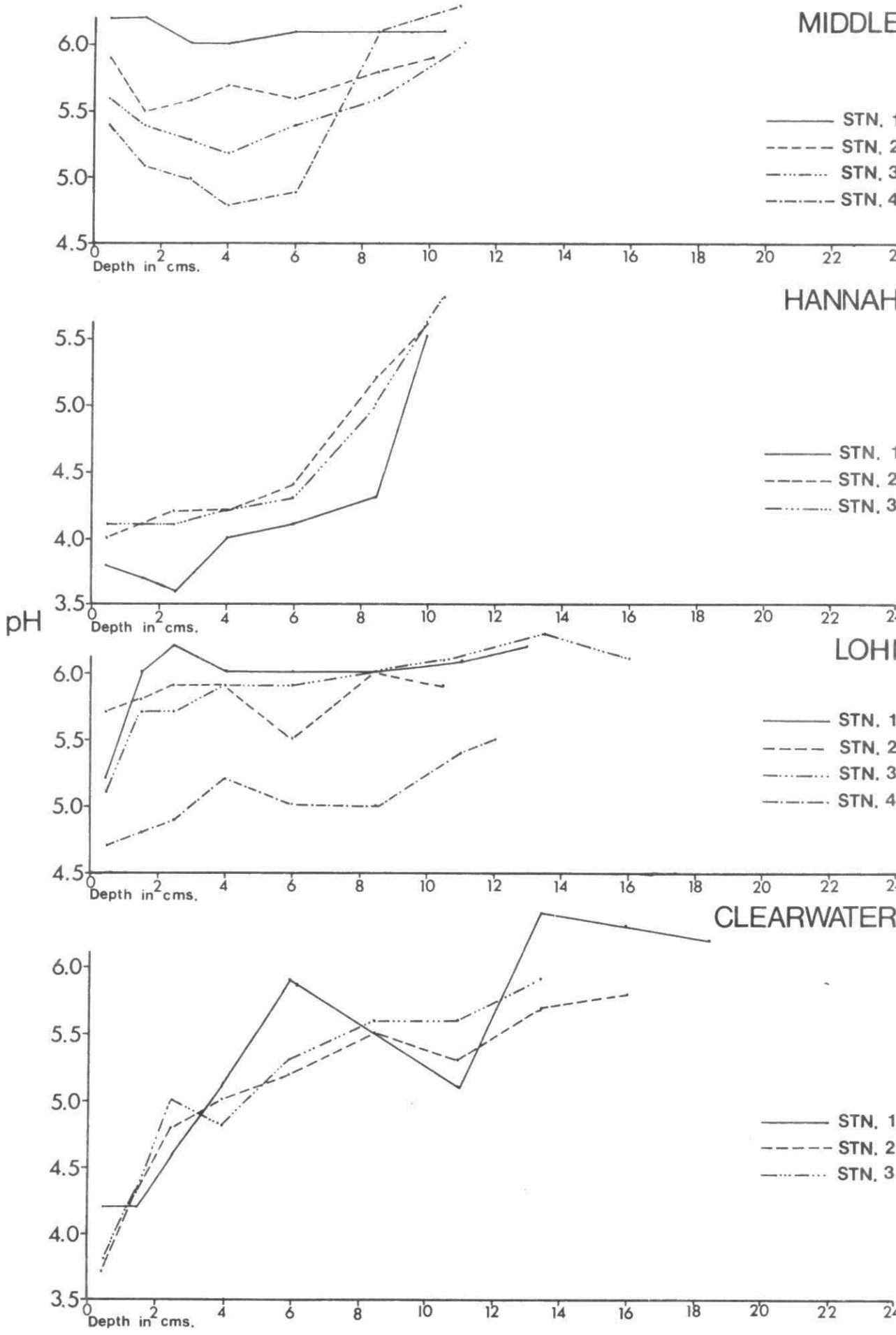


Figure 15: Sediment NICKEL Profiles

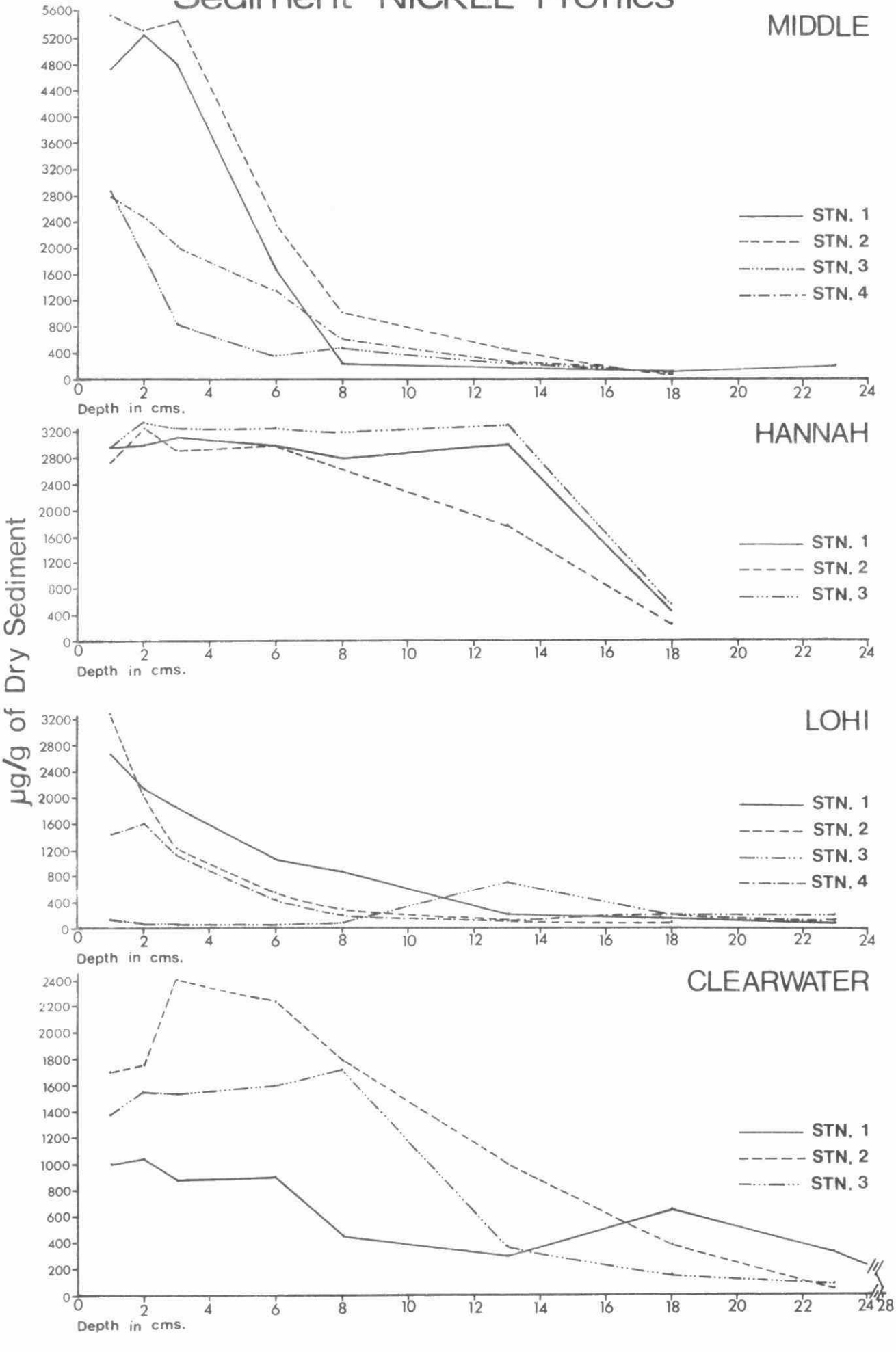
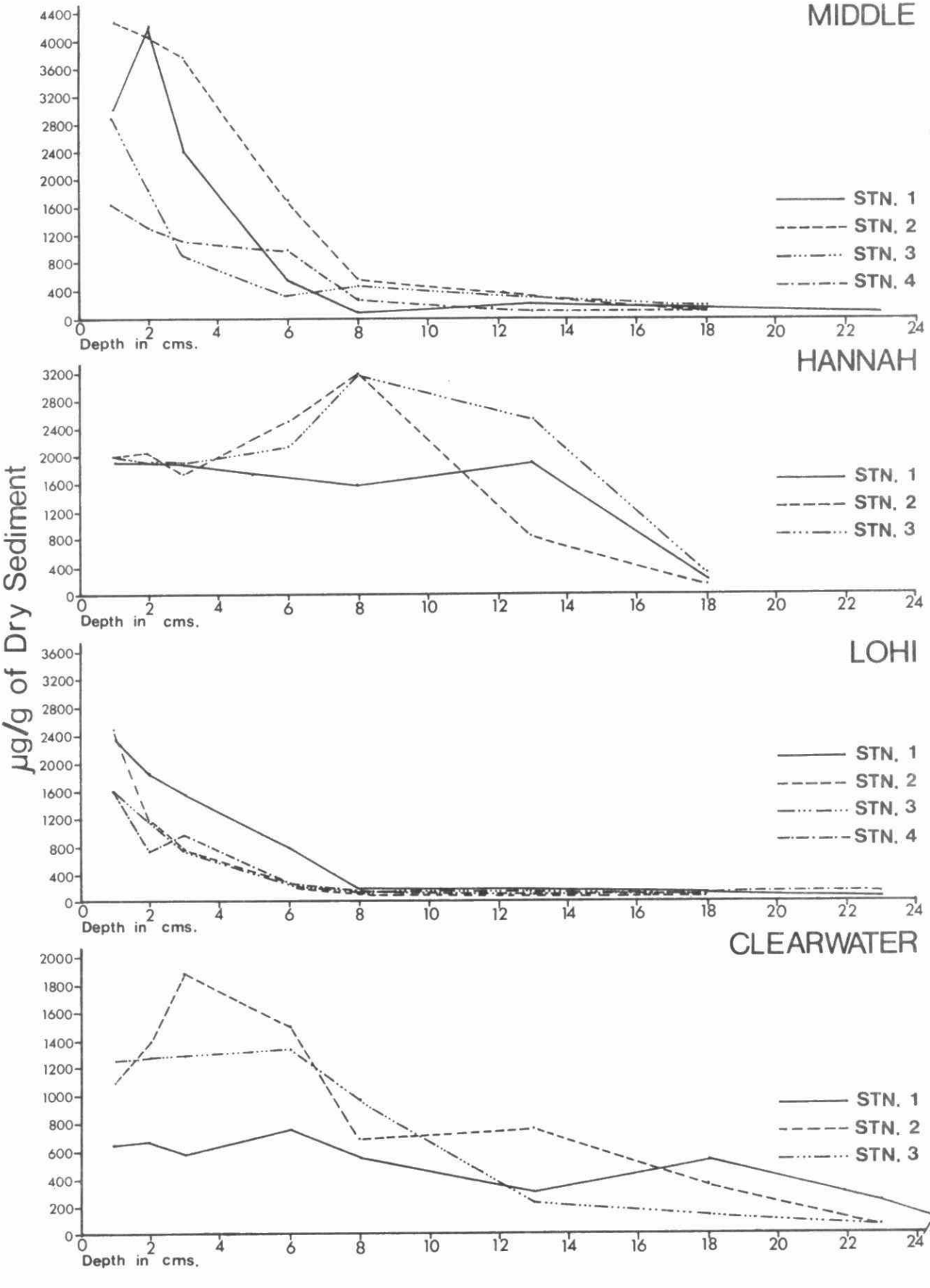


Figure 16: Sediment COPPER Profiles



3. Biological Parameters

a) Microbiology

Micro-organisms, a diverse group including bacteria, yeasts and molds, form an important link in the aquatic food chain. They can be both primary and secondary producers (Sorokin and Kadota, 1972) but their key function is as decomposers that recycle organic matter that would otherwise be unavailable to the higher levels of the food chain. Additionally, they are preyed upon by sediment detritavores and some zooplankters.

Pre-treatment composition and population levels for yeasts and molds were considered normal for oligotrophic lakes (Thompson and Wilson, 1973). Ammonia oxidizing bacteria were not detected indicating retarded cycling of nitrogen in the lakes. Sulphate reducers aerobic heterotrophs non-acidophilic sulphur-oxidizers and coliforms were also scarce in the study lakes when compared to eutrophic Maclean Lake (8 km N.E. of Coldwater, Ont.). However, counts of acidophilic sulphur oxidizers were higher in the study lakes than Maclean Lake as expected, since Maclean Lake has a neutral pH.

Post-treatment 1973 data indicate a significant increase in aerobic heterotrophic bacteria in the water column of the treated lakes (Table 13 In fact, levels equaled or exceeded those found in Maclean Lake. Sediment populations remained relatively constant.

Table 13: Ranges of aerobic heterotrophic bacterial counts in study lakes and Maclean Lake during autumn 1973. (Counts per 100 ml or per gm wet sediment)

	EXPERIMENTAL LAKES			
	Middle		Lohi	
	Preliming	Postliming	Preliming	Postliming
Surface	-	120000 - 150000+	720 - 3400	8700 - 60000
Bottom	340	56000 - 150000+	910 - 1200	6800 - 54000
Sediments	275000	160000 - 170000	131000	27000 - 350000

	CONTROL LAKES		
	Hannah	Clearwater	Maclean
Surface	420 - 2800	170 - 13000	2000 - 156000
Bottom	110 - 1700	200 - 2600	7300 - 8400
Sediments	92000 - 430000	130000 - 270000	210000

The pH elevation and heavy metal reduction may have removed many of the inhibitors of bacterial growth (Thompson and Wilson, 1973). Although the heterotrophic bacteria were characterized as acid tolerant (aciduric), growth at the low pre-treatment pH had been retarded. Levels of sulphate reducers and non-acidophilic sulphur oxidizers also showed increased after liming whereas populations of yeasts, molds, coliforms and ammonia oxidizers remained constant. In general, the microbial level of the food chain showed a rapid positive response to the altered water conditions of the treated lakes in 1973.

In 1974 counting techniques were changed (Thompson and Croll, 1974). Results cannot be directly compared to 1973 values but did continue to reflect the initial response to liming. Coliforms were not analyzed but blue-green algae were examined because of their importance in nitrogen fixation. Blue-greens were also analyzed during routine phytoplankton sampling (following section). Minnow Lake, a shallow eutrophic lake located within Sudbury, and oligotrophic Harp Lake, 10 km N.E. of Huntsville, were included for comparison.

The treated lakes supported significantly higher levels of heterotrophic bacteria than the controls. (Tables 14(a), (b); Figure 17). In fact, geometric mean values of heterotrophs in the treated lake were slightly higher than those in eutrophic Maclean and Minnow lakes. Blue-green levels were also higher in treated than control lakes (Figure 20) completely selective and colonies of green algae were also isolated. Populations of aciduric bacteria were lower in the surface waters of the treated lakes (Tables 14(c), (d); Figure 18). The hetero-trophic: aciduric ratio, a good indicator of gross changes in the water column, reflects the altered water chemistry of the treated lakes (Table 14(f).

Sediment results were variable but several trends are discernible. Levels of sulphate reducers were generally higher in the treated lakes (Table 14(c); Figure 19). Sulphur oxidising and ammonia ozidizing bacteria remained at low levels in all study lakes. No significant trends were shown by either aerobic or anaerobic bacterial populations. The microbiology of the study lakes is discussed in more detail in Thompson and Croll (1974).

Table 14: Statistical Results of Lake to Lake Variation in Microbiological Parameters.

a.

Meter below surface Heterotrophic Plate Count	Clearwater	Lohi	Hannah	Middle
Clearwater	-	s	-	s
Lohi	-	-	s	-
Hannah	-	-	-	s
Middle	-	-	-	-

c.

Meter below surface Aciduric Values	Clearwater	Lohi	Hannah	Middle
Clearwater	-	s	-	s
Lohi	-	-	-	-
Hannah	-	-	-	-
Middle	-	-	-	-

b.

Meter above bottom Heterotrophic Plate Count				
Clearwater	-	s	-	s
Lohi	-	-	s	-
Hannah	-	-	-	s
Middle	-	-	-	-

d.

Meter above surface Aciduric Values				
Clearwater	-	-	-	-
Lohi	-	-	-	-
Hannah	-	-	-	-
Middle	-	-	-	-

e.

Sediment Sulphate Reducers				
Clearwater	-	-	-	-
Lohi	-	-	-	-
Hannah	-	-	-	s
Middle	-	-	-	-

f.

HPC: Aciduric Ratio	MBS	MAB
Clearwater	0.176	0.276
Lohi	136	26.3
Hannah	0.265	0.176
Middle	184	20.3

s indicates a difference at .01 level of significance.

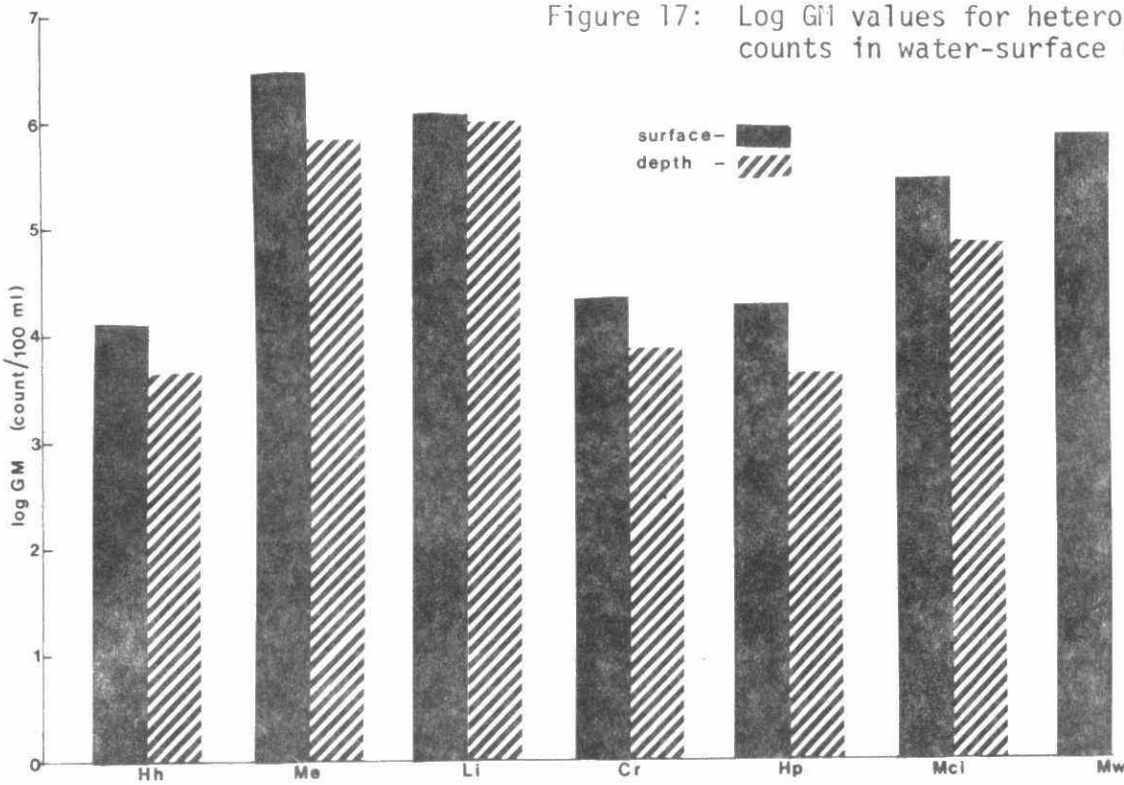


Figure 17: Log GM values for heterotrophic plate counts in water-surface and depth levels.

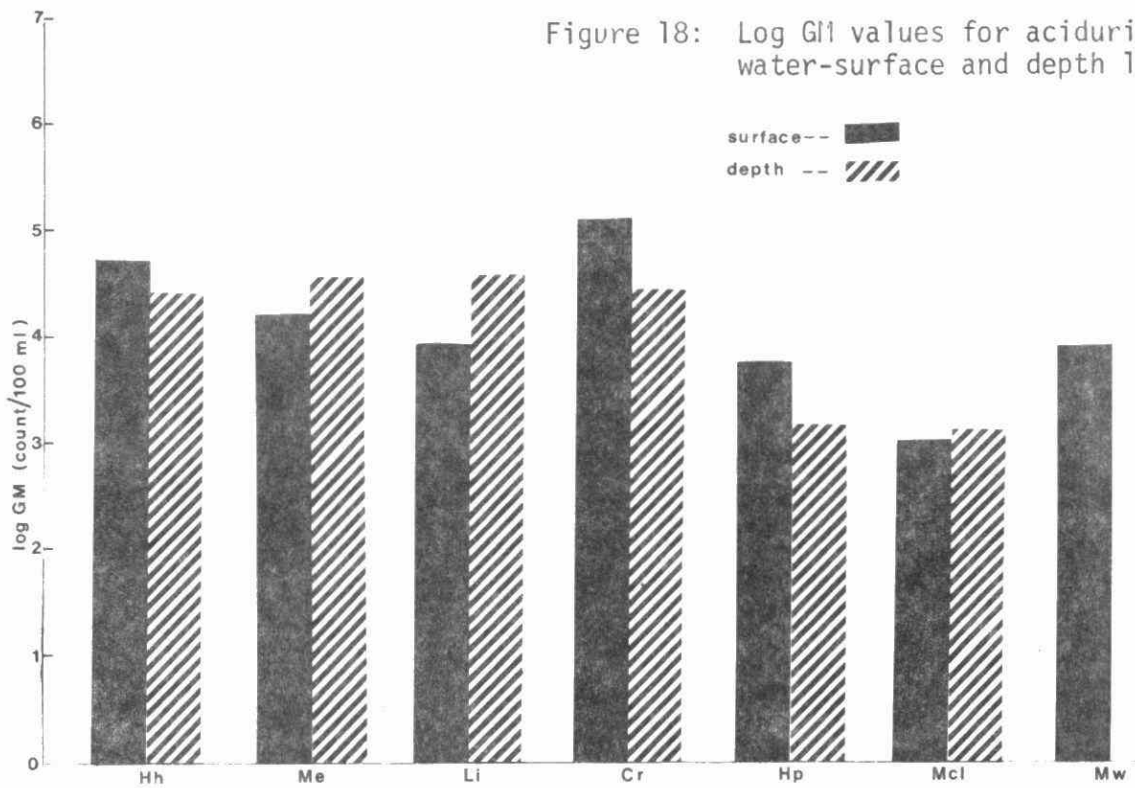


Figure 18: Log GM values for aciduric counts in water-surface and depth levels.

Figure 19: Log GM values for sediment SO_4 reducers

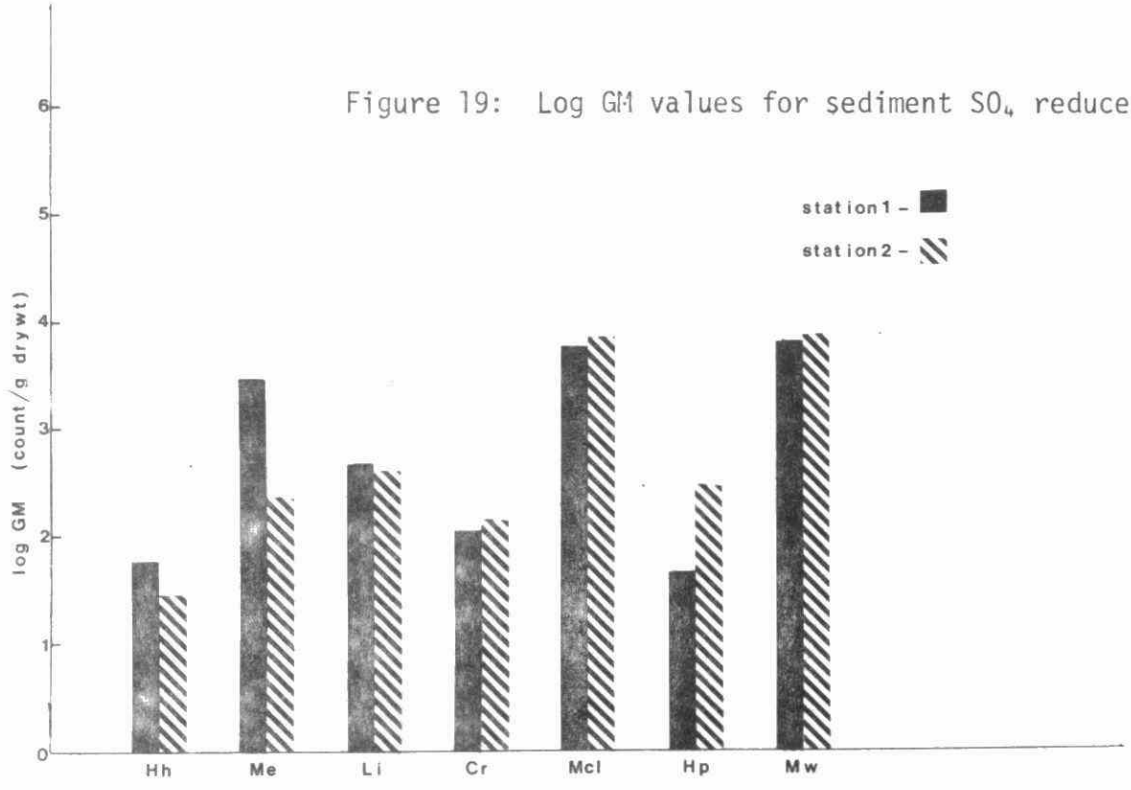
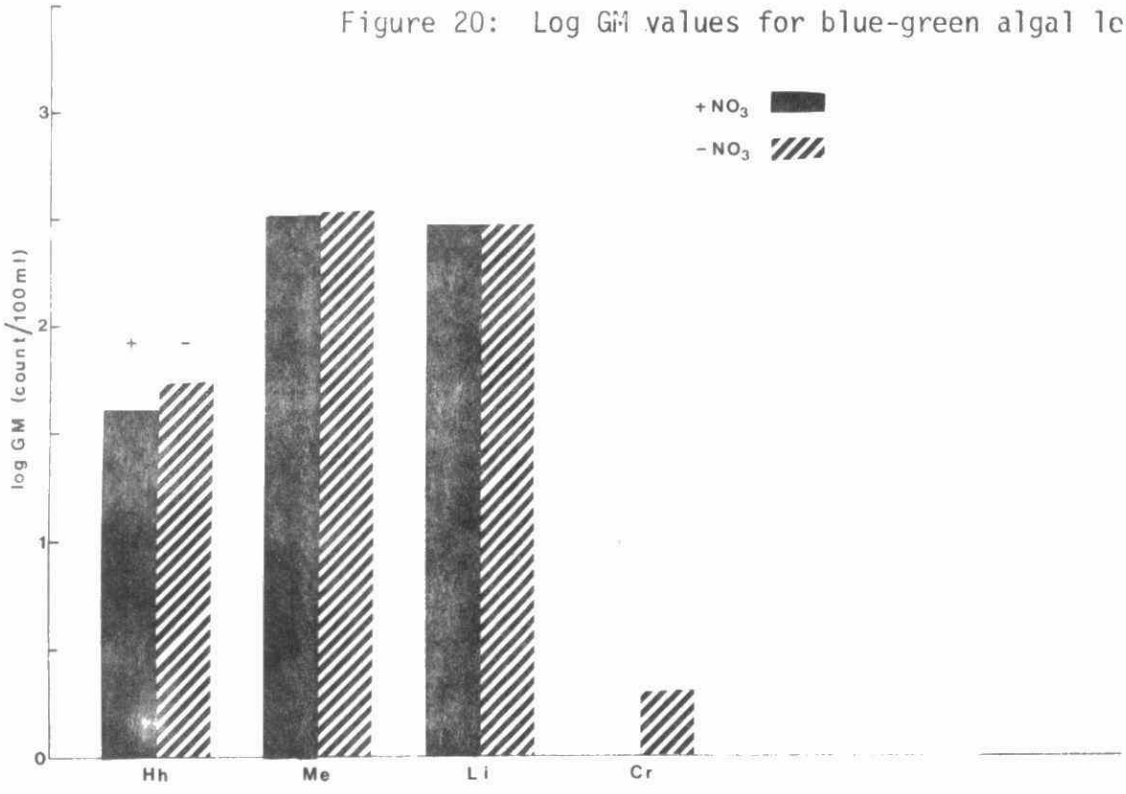


Figure 20: Log GM values for blue-green algal levels.



b) Phytoplankton, Chlorophyll a, Primary Production

Free floating algae are collectively known as phytoplankton. Together with some of the bacteria, they form the producer base of the food chain and are fed upon by higher level consumers (Prescott, 1961). The classification scheme employed for phytoplankton was taken from Prescott (1961) and is presented on the Key to Figure 21.

Standing crop of phytoplankton was measured using two methods. The areal standard unit method was employed because it is preferred when relating standing crop to primary production (Paasche, 1960 in Johnson, Michalski and Christie, 1970). The chlorophyll a method was used because, together with total phosphorus and Secchi disc values, chlorophyll a levels provide a widely accepted means of classifying lakes according to trophic status. Estimates of primary production using the ^{14}C technique, have been used to measure the assimilation rate of carbon by phytoplankton, and hence to estimate daily or annual production (Ruttner, 1953).

Numbers and taxonomic composition (to Class) of the phytoplankton in the study are summarized in Figure 21. Mean values of standing stock (Table 15) are separated into summer and fall periods to allow better comparison between 1974 and 1973, when fall sampling only was done (beginning in July, 1973).

Table 15: Phytoplankton Stocks in the Study Lakes (1973/1974) in asu ml^{-1}

Lake	1973 Fall Pretreatment		1973 Postreatment		1974 Summer[1]		1974 Fall[2]	
	$\bar{y}$	range	$\bar{y}$	range	$\bar{y}$	range	$\bar{y}$	range
Hannah	87(15)	41-120	-	-	413(6)	157-748	155(6)	29-473
Middle	135(8)	32-320	14(7)	1-46	135(9)	3-1091	676(6)	261-1151
Clearwater	139(15)	54-193	-	-	231(4)	49-408	201(6)	70-542
Lohi	210(11)	52-545	9(3)	5-13	99(5)	8-330	1031(6)	173-4757

Numbers in brackets refer to number of samples.

$\bar{y}$ = mean value

1. Weeks 1-9 of 1974 (Lohi Lake was limed between weeks 9 & 11, 1974).
2. Weeks 11-21 of 1974

Pretreatment mean values were generally slightly lower than reported means for other oligotrophic Shield lakes (Michalski, Johnson and Veal, 1973) as summarized in Table 16. However, values were similar to other acidic lakes in the Sudbury region (Conroy, 1971; Johnson and Owen, 1966) as summarized in Table 16.

Table 16: Phytoplankton Stocks in Some Ontario Lakes (in asu ml^{-1}).

Lake	mean	Range	Trophic Status	pH	Source
Joseph	402	31-1153	oligotrophic	-	Michalski et al (1973)
Rosseau	479	54-1880	oligotrophic	-	"
Georgian Bay	226	7-708	oligotrophic	-	"
Erie (west)	3190	1022-7147	eutrophic	-	"
Gravenhurst Bay	2686	134-6402	eutrophic	-	"
Lakes in Sudbury Area					
Camp Ten	2061	310-4845	-	7.0	Conroy (1971)
Little Penage	535	254-856	-	7.2	"
George	43	22-55	-	5.5	"
Norway	49	one sample	-	3.2	Johnson et al (1966)
Moose	25	20-31	-	4.0	"
Carson	293	173-413	-	5.0	"

In 1973 prior to treatment all lakes showed fall dominance of green algae (Chlorophyta) and flagellates (Pyrrhophyta), with the yellow-greens (Chrysophyta) assuming some minor importance in the control lakes. Dominant genera included *Peridinium*, *Cryptomonas*, *Oocystis*, and three unidentified Chrysophytes. Conspicuously absent were significant levels of diatoms (Bacillariophyceae) and blue-green algae (Myxophyceae). The results agree very closely with Swedish acid lakes in which *Peridinium*, *Gymnodinium*, *Oocystis* and *Ankistrodesmis* (Pyrrhophyta and Chlorophyta) consitituted the bulk of the biomass at pH 4.0 (Almer et al, 1974). Near Sudbury, Myslik (unpublished data) found Daisy Lake (pH 4.1) to also be dominated by Pyrrhophyta (*Gymnodinium* and *Peridinium*) and Chlorophyta (*Chlorella*) in August 1969.

The dominance of flagellates and green algae is thought to be an atypical situation indicative of stress conditions. Schindler and Holmgren (1971)

found yellow-green algae (Chrysophyta) to be dominant in mid-summer in eight lakes in the ELA. Using their classification scheme (modified from Findenegg, 1964), the study lakes should have fallen into class C; shallow weakly stratified lakes dominated by diatoms and yellow-greens (Bacillariophyceae and Chrysophyceae respectively).

In Middle Lake immediately after liming, phytoplankton standing crop decreased from 230 to 46 asu ml^{-1} (Figure 21a). Since the control lakes exhibited no similar decrease, the decline in Middle was attributed to treatment effect. This agrees with the results of Waters (1956) who found that liming decreased the phytoplankton standing stock. Hydrated lime is known to be algicide, lethality being caused by changes in CO_2 or pH (Whipple 1948 in Waters 1956). It is also possible that lime coagulates and precipitates the phytoplankton out, in much the same way as suspended matter, metals and nutrients are removed (Cohen and Hannah, 1971). Although Lohi Lake phytoplankton also decreased following treatment, it had already declined significantly prior to liming, probably in accord with the natural seasonal periodicity.

In 1974 all study lakes were characterized by a shift in dominance to Chrysophyta (yellow-greens), and an increase in phytoplankton standing crop. As Table 15 shows, mean values increased approximately twofold from fall 1973 to fall 1974 in the control lakes, Hannah and Clearwater. Since extensive background data did not exist, the increase was ascribed to natural causes. In the same time period the treated lakes, however, increased more than fivefold.

The shift in dominance was most marked in the treated lakes, the dominant genera being *Dinobryon* and an unidentified Chrysomonad (Appendix F). This agrees with the observations of Waters (1956), who found *Dinobryon sertularia* Ehrenberg to appear and increase in numbers one year after liming. Of particular interest was the appearance in the study lakes of diatoms (Bacillariophyceae - mostly *Navicula* and *Nitzchia*) and blue-green algae (Myxophyceae - *Oscillatoria*) which were numerically prominant in the spring in Middle Lake and which remained in low numbers throughout 1974 (Figure 21a). This agrees with Almer et al (1974) who reported that at a pH >5, diatoms and blue-greens begin to contribute significantly to algal biomass. Myslik (unpublished data) reported yellow-greens (*Dinobryon*) and diatoms (*Nitschia, Cyclotella, Synedra, Navicula*) to be dominant in Richard Lake (pH 6.8 - 7.0) near Sudbury. Conroy (1971) reported diatoms (*Asterionella*) and blue-greens generally dominant in nine lakes (pH 5.1 - 7.2) in the Sudbury region.

In Lohi Lake during 1974, blue-green algae and diatoms did not appear until the end of June and at no time assumed dominance. However, the fact that the blue-greens present were not nitrogen fixers is of concern as this retards nitrogen cycling in the lakes.

In 1974, in the control lakes, the shift in dominance to yellow-greens was not as well defined. Early in the summer, Hannah Lake was dominated by the yellow-green *Dinobryon* but this shifted in mid-summer to an approximately equal composition of an unidentified Chrysophyte, the desmid *Cosmarium* and the green alga *Chlamydomonas*. Low levels of diatoms were also found. In Clearwater in 1974, the generic composition was the most diverse of all lakes, major genera being the flagellates (*Peridinium* and *Cryptomonas*) and two unidentified Chrysophytes. This composition does not generally agree with that found in acid Swedish lakes as reported by Almer et al (1974).

As opposed to the immediate adverse effect observed in the fall 1973 liming, the July 5th 1974 liming of Lohi Lake saw a threefold increase in total phytoplankton standing stock by July 11th. It is not known if stocks decreased immediately after treatment and recovered rapidly, or were not affected by the liming, because the biweekly analysis was not sensitive enough to detect this. However, the substantial levels (330 asu ml^{-1}) one week after treatment suggest that incremental additions may exert less of a lethal effect on the algae than a large, single dose application. This contradicts the findings of Waters (1956) who observed that even incremental additions reduced phytoplankton standing stock.

In summary, it appears that the phytoplankton respond positively soon after liming. Significant increases in standing stock occur and the generic composition begins to approach the more typical dominance by Chrysophyceae and Bacillariophyceae as reported by Schindler and Holmgren (1971) in the ELA.

Pretreatment means of chlorophyll a ranged from 0.55 to 1.6 mg m^{-3} indicating the extremely oligotrophic nature of the lakes. Dillon and Rigler (1974b)present data on mean summer chlorophyll a levels of North American lakes showing a range of 0.3 to 41 mg m^{-3} and reported 19 lakes in S. Ontario to range from 0.75 to 2.7 mg m^{-3}. Conroy (1971) found chlorophyll a values in nine lakes in the Sudbury vicinity to range between 0.9 and 7.5 mg m^{-3}.

Values declined in all study lakes in 1974 (Table 17) but because levels were near the detection limit, interpretation is tenuous. There did not seem to be a good correspondence between chlorophyll a levels and values of asu ml^{-1}, nor was there a uniform seasonal pattern in chlorophyll a values (Figure 21).

Table 17: Chlorophyll a in the Study Lakes 1973/1974 (mg m^{-3})

Lake	1973 [chl. a]		1974 [chl. a]	
	mean	range	mean	range
Hannah	0.55	0.3-1.7	0.44	0.1-1.0
Middle	0.91	0.3-1.9	0.87	0.2-2.0
Clearwater	1.4	0.3-3.2	0.50	0.2-1.3
Lohi	1.6	0.5-3.9	0.87	0.2-2.1

Primary production results were not available in time for inclusion in this report and will be published at a later date.

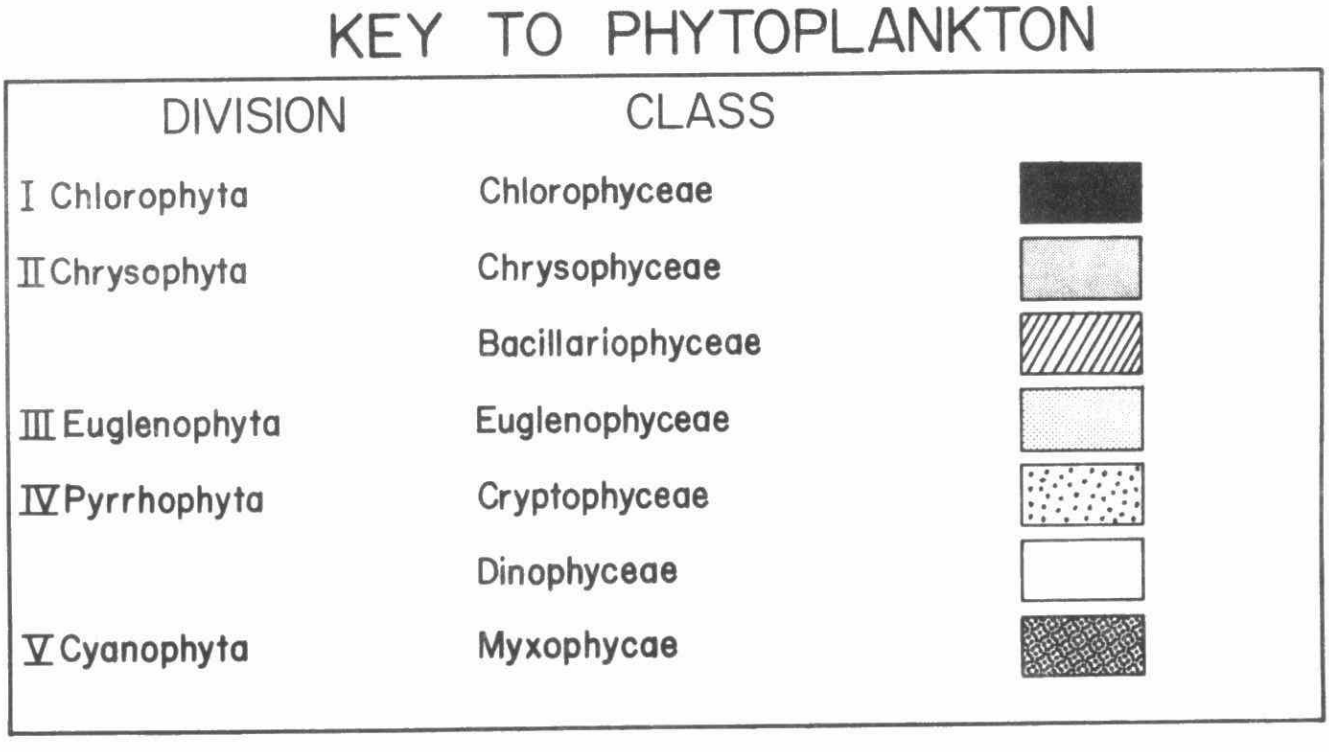
Figure 21: Phytoplankton Standing Stock and Taxonomic Composition.

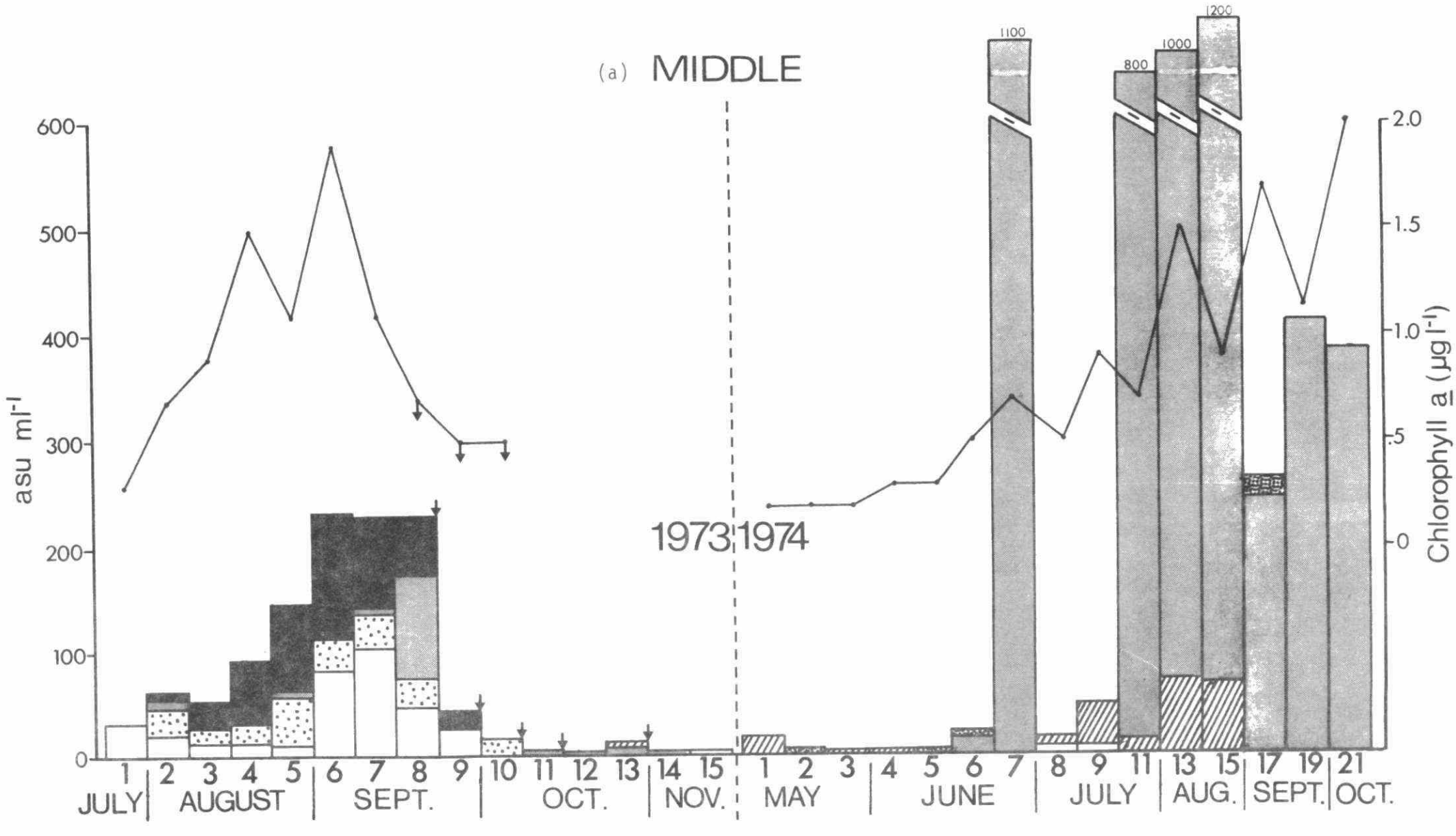
(a) Middle Lake

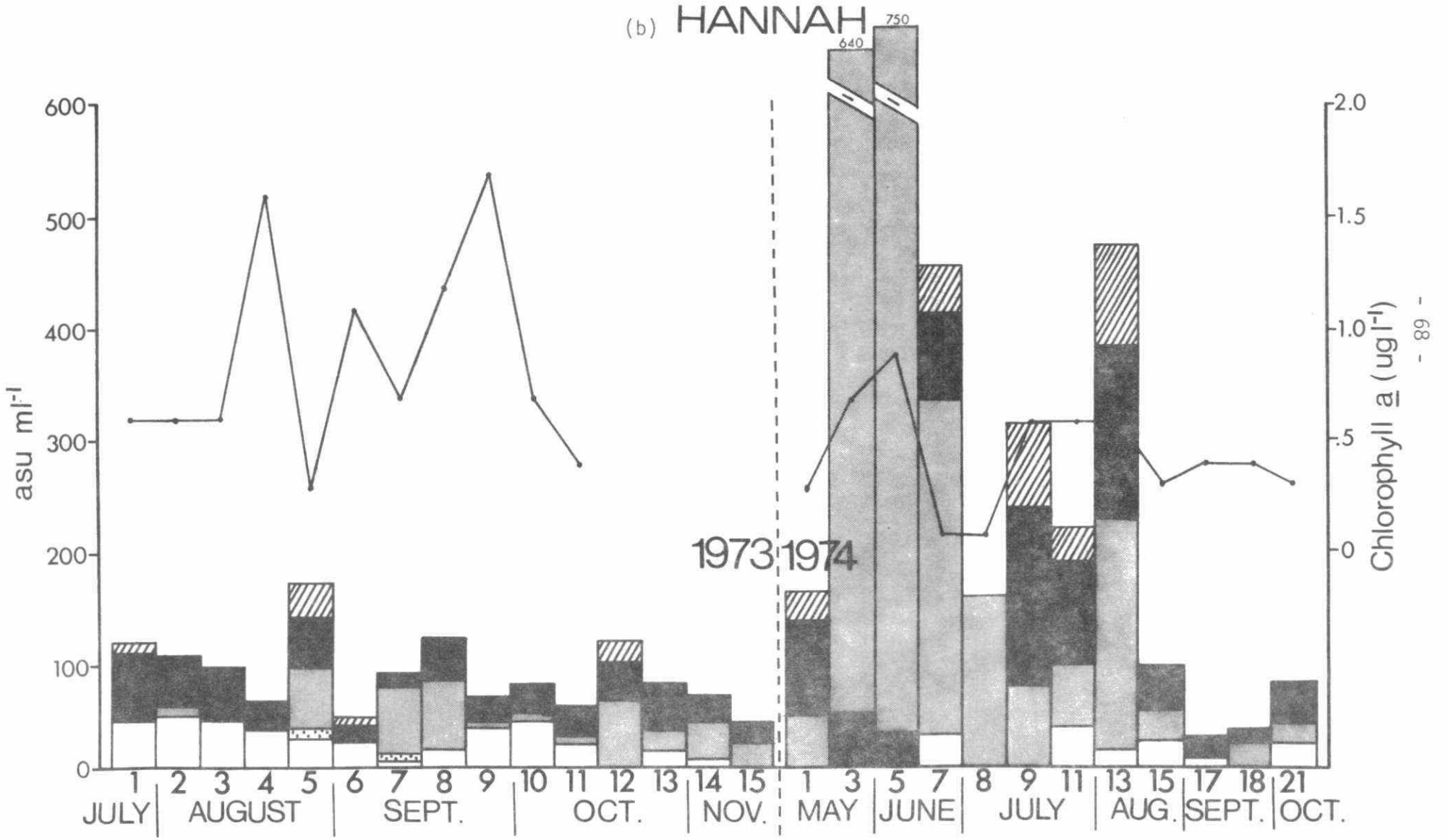
(b) Hannah Lake

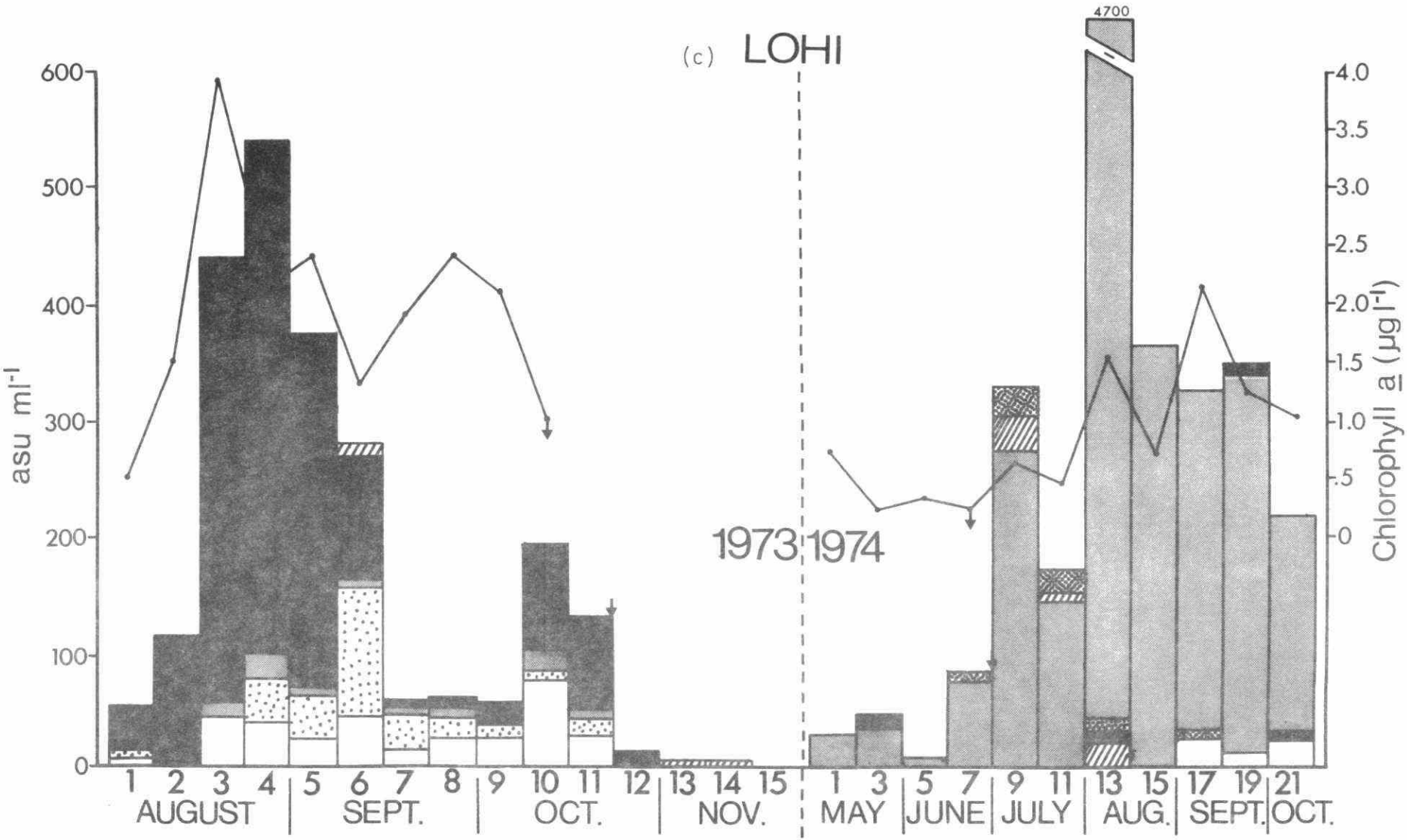
(c) Lohi Lake

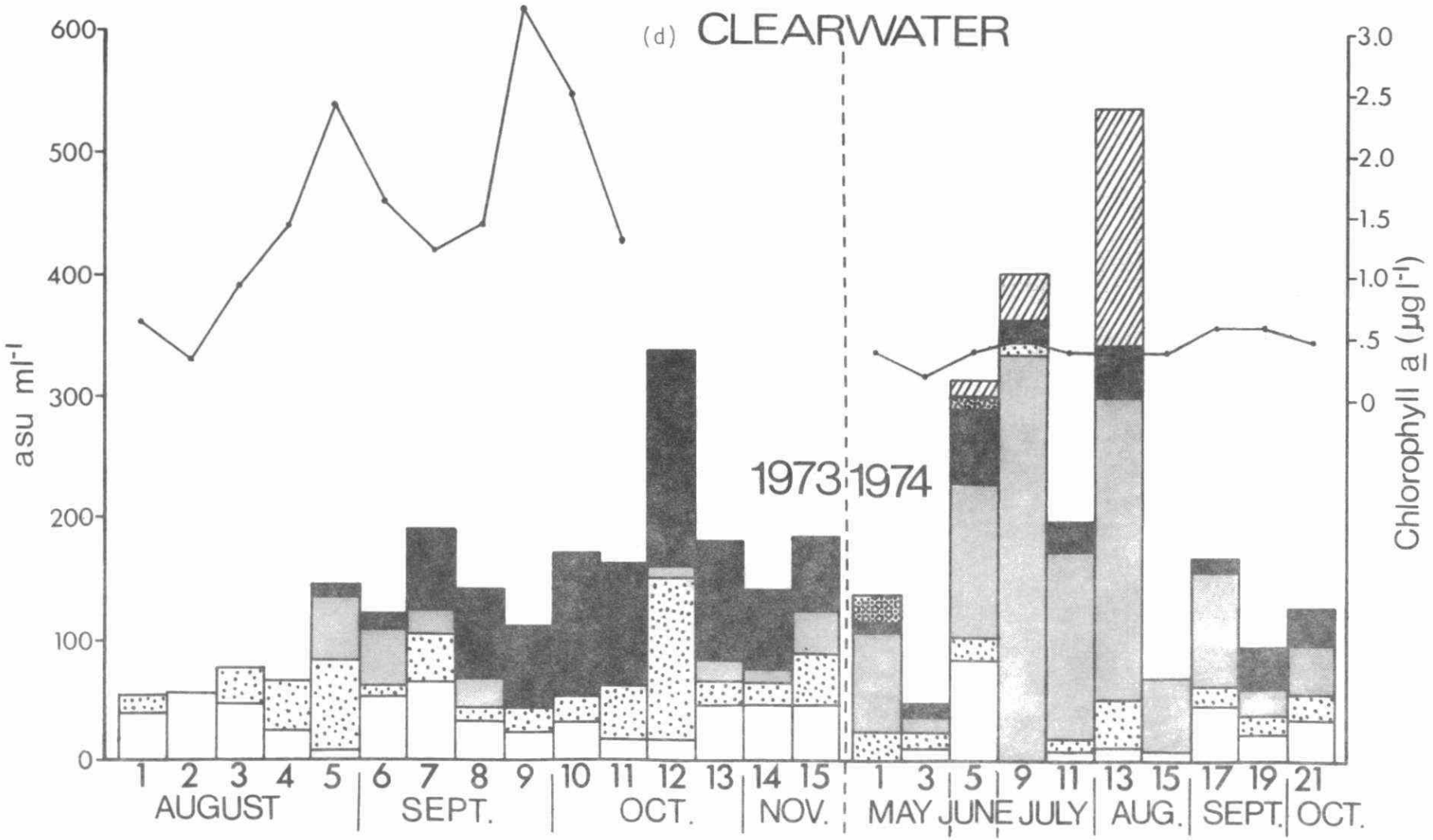
(d) Clearwater Lake




(a) MIDDLE
1973 1974
asu ml-1
Chlorophyll a (µg l-1)
600
500
400
300
200
100
0
2.0
1.5
1.0
.5
0
1100
1000
800
1200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 2 3 4 5 6 7 8 9 11 13 15 17 19 21
JULY AUGUST SEPT. OCT. NOV. MAY JUNE JULY AUG. SEPT. OCT.


(b) HANNAH
640
750
asu ml-1
Chlorophyll a (ug l-1)
600
500
400
300
200
100
0
2.0
1.5
1.0
.5
0
1973
1974
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
JULY AUGUST SEPT. OCT. NOV.
1 3 5 7 8 9 11 13 15 17 18 21
MAY JUNE JULY AUG. SEPT. OCT.


(c) LOHI
4700
asu ml-1
Chlorophyll a (µg l-1)
600
500
400
300
200
100
0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
.5
0
1973
1974
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
AUGUST
SEPT.
OCT.
NOV.
1 3 5 7 9 11 13 15 17 19 21
MAY
JUNE
JULY
AUG.
SEPT.
OCT.


(d) CLEARWATER
asu ml⁻¹
Chlorophyll a (µg l⁻¹)
600
500
400
300
200
100
0
3.0
2.5
2.0
1.5
1.0
.5
0
1973
1974
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
AUGUST SEPT. OCT. NOV.
1 3 5 9 11 13 15 17 19 21
MAY JUNE JULY AUG. SEPT. OCT.

c) Zooplankton

Zooplankton are mostly first-level consumers, grazing phytoplankton, bacteria and organic debris. They are in turn fed upon by other consumers, notably immature insect larvae and fish (Ruttner, 1953).

Numbers and taxonomic composition of zooplankton in the study lakes for 1973/1974 are shown in Figure 22. Pretreatment (1973) mean numbers cm^{-2} fell at the low end of those reported by Patalas (1971) for five lakes of similar morphometry in the ELA, as outlined in Table 18. .

Table 18 : Comparison of zooplankton numbers in study lakes and five lakes in ELA.

Lake	Area (ha)	Max. depth (m)	Total numbers cm^{-2} Mean		Maximum
251	100	17.3	54		-
224	25.4	16.7	11		-
189	28.8	15.8	46		-
226	21.8	12.2	10		-
163	15.7	8.5	46		-
Hannah	18	7.5	0.75	1973	1.7
			0.47	1974	2.6
Middle	21	14	9.8	1973	69
			0.49	1974	2.6
Clearwater	77	19	5.8	1973	20
			17	1974	56
Lohi	29	17	48	1973	112
			1.5	1974	6.3

Number of zooplankton cm^{-2} in Sudbury lakes calculated by multiplying number m^{-3} by $\bar{z}$ (m)/10^4.

Conroy (1971) studied nine lakes in the vicinity of Sudbury (pH 5.5 - 7.0) and found maximum zooplankton numbers of 3000 m^{-3}. However, the seasonal variability in zooplankton abundance in the study lakes (up to three orders of magnitude) indicates the difficulty of generalizing about "typical" zooplankton numbers. Schindler and Noven (1971) found seasonal fluctuations of 150,000 m^{-3} in rotifers, 45,000 m^{-3} in cyclopoids and 10,000 m^{-3} in cladocerans. Also, it must be noted that the Sudbury values are based on sampling with a Wisconsin net. Plankton tow-nets may clog and be avoided by zooplankton (UNESCO, 1968). Their filtering efficiency can vary

from 40% - 100% (Rawson, 1956 in Patalas, 1971) hence the quantitative values presented are approximate and indicate gross, relative changes in numbers only.

In all the study lakes the dominant zooplankton group was Cladocera (mostly *Bosmina longirostris* and *Chydorus sphaericus*). Copepoda, the next most abundant group, was made up mostly of nauplius larvae, a morphological term (not taxonomic) denoting an immature copepod. Similarly, a copepodid is the immature stage prior to adult. *Cyclops vernalis*, a cyclopoid, was the only adult copepod that appeared consistently in the study lakes. The lack of adult copepods is not unique to the Sudbury lakes. Schindler and Noven (1971) found adult cyclopoids (*Cyclops sp.* and *Tropocyclops sp.*) to be the least abundant copepod form in two lakes in the ELA. Similarly, they also found the calanoid copepods to be mostly in the immature copepodid stages. Rotifers were present in 1973 in all study lakes but only assumed numerical importance in Lohi Lake (Appendix G.)

Patalas (1971) reported a community classification scheme for 45 lakes in the ELA in which the dominant factors affecting the zooplankton species composition were lake surface area and maximum depth. Applying this scheme, the Sudbury lakes should have had one cyclopoid and one diaptomid (both Copepoda) co-dominant. In fact, the cladoceran *Bosmina longirostris* was dominant and very few diaptomids were found. However, Patalas also reported *Bosmina longirostris* to occur in 91% of the 45 lakes and to be dominant in 18% of them (a species was considered dominant if it made up > 10% of all crustacean zooplankton numbers).

Schindler and Noven (1971) found Lake 122 in the ELA to have a more diverse assemblage of zooplankton than the four Sudbury lakes although morphometrically similar (A_o = 12.2 ha., $\bar{z}$ - 7.2 m). The lake was dominated by the calanoid copepod *Diaptomus minutus* as opposed to dominance by cladocerans observed in the Sudbury lakes.

The crustacean zooplankton dominance patterns observed in the study lakes perhaps correspond more closely to those reported by Almer et al (1974) for acidic lakes in Sweden. They reported that as the lakes became more acidic, the zooplankton diversity decreased and that in lakes of low pH (as low as 3.3) the only crustacean zooplankton present were *Bosmina* and *Diaptomus*. Rotifers were also found in the low pH waters. Stockinger and Hays (1960), found the rotifer *Keratella* and the cladoceran *Scapholeberis* to be dominant in an acidic

(pH 3.6) strip-mine lake.

Numbers of the dominant zooplankter (*Bosmina longirostris*) in the study lakes fluctuated but generally showed a single, prolonged summer population maximum. Definite spring and fall population peaks have been reported by Anderson and Armstrong (1966) for lakes in Dakota and by Schindler and Noven (1971) for lakes in the ELA; however, single population maxima have been reported (Pennak 1953).

The fall 1973 liming brought about population declines that were greater than the natural seasonal decreases observed in the control lakes. This may be due to two factors: a lethally rapid change in pH and a removal of zooplankton food sources (phytoplankton and suspended organic matter) by a precipitation mechanism. It was expected that populations would increase the year after treatment as observed by Waters (1956) in his study on the effects of liming on acid bog lakes. However, populations remained low in both treated lakes in 1974 whereas control lake zooplankton numbers remained relatively stable or increased (Table 18, Appendix G).

Lack of food was probably not the cause for the failure of the zooplankton to return because phytoplankton and bacterial levels were higher in 1974 than 1973 in both treated lakes. The most plausible explanation is that the fall liming eliminated much of the adult population before reproduction occurred. Cladocera reproduce in the fall by parthenogenesis, laying over-winter resting eggs. The spring population is also augmented by surviving over-wintering adult females. However, the fall liming affected both adults and eggs thus reducing next years cohort. Copepods reproduce sexually, *Cyclops vernalis* year round (Pennak 1953); hence their low numbers are probably due to adult mortality following liming.

Not all liming adversely affected the zooplankton. In 1973, the September 25th liming of Middle Lake raised the pH of the surface water 0.8 units, yet total numbers of zooplankton did not change, although dominance shifted from *Bosmina longirostris* to *Chydorus sphaericus*. In 1974, the July 5th liming of Lohi Lake raised the pH 0.6 units. Instead of a decline in numbers, the population tripled and remained higher throughout the summer. This suggests that liming in incremental doses might affect the zooplankton less than a large single application.

In summary, the pretreatment situation of low diversity and high relative numbers of a few dominant species seemed to agree with general

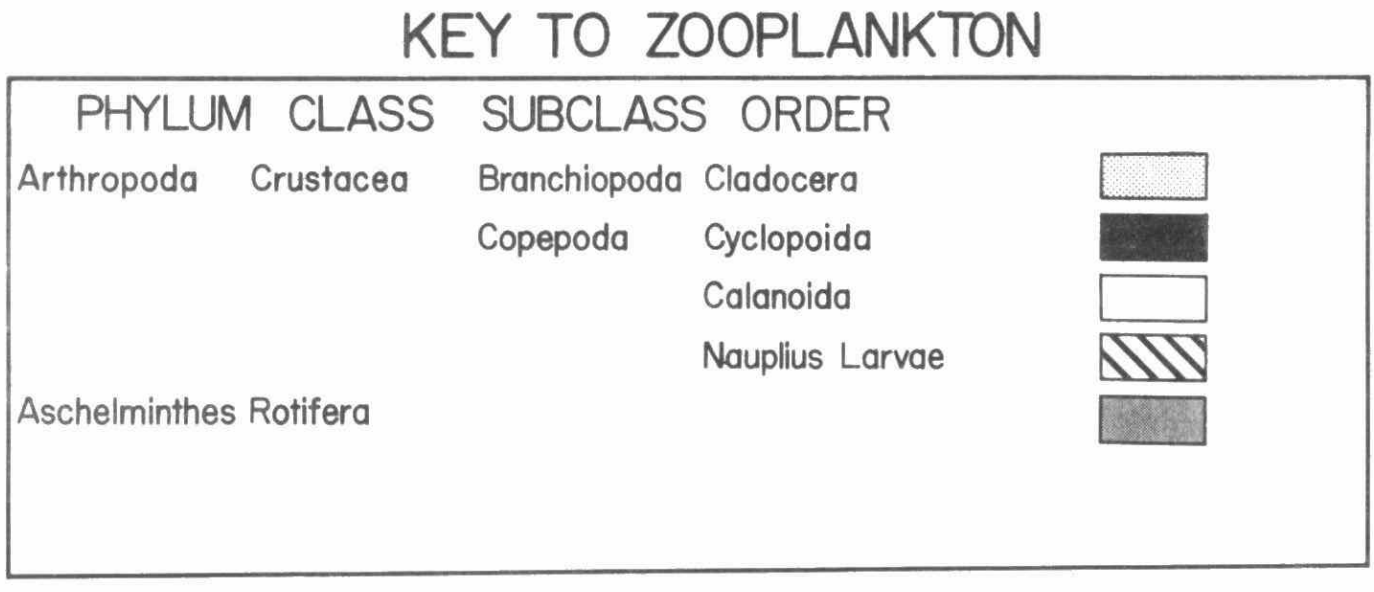
Figure 22: Zooplankton Standing Stock and Taxonomic Composition

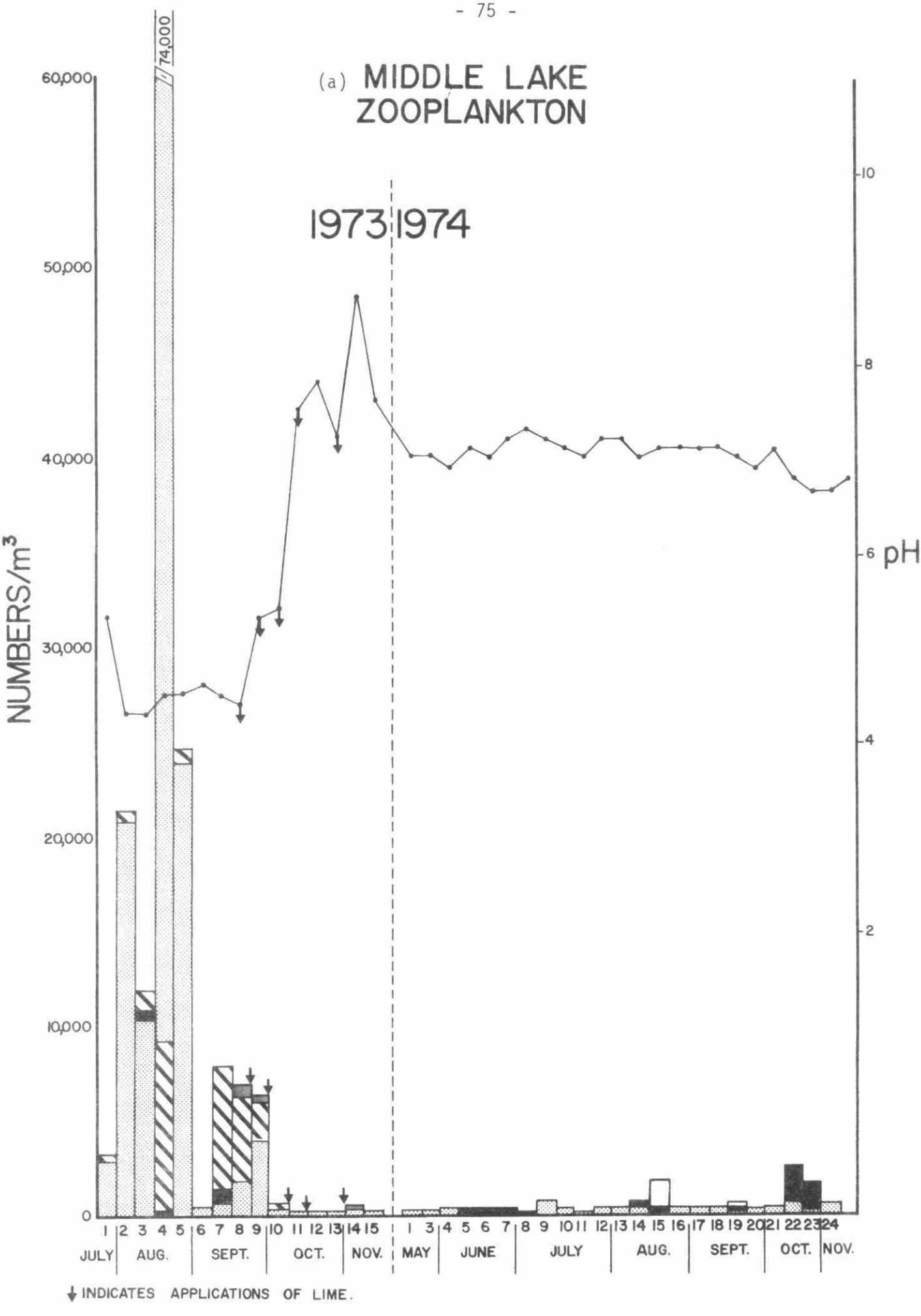
(a) Middle Lake

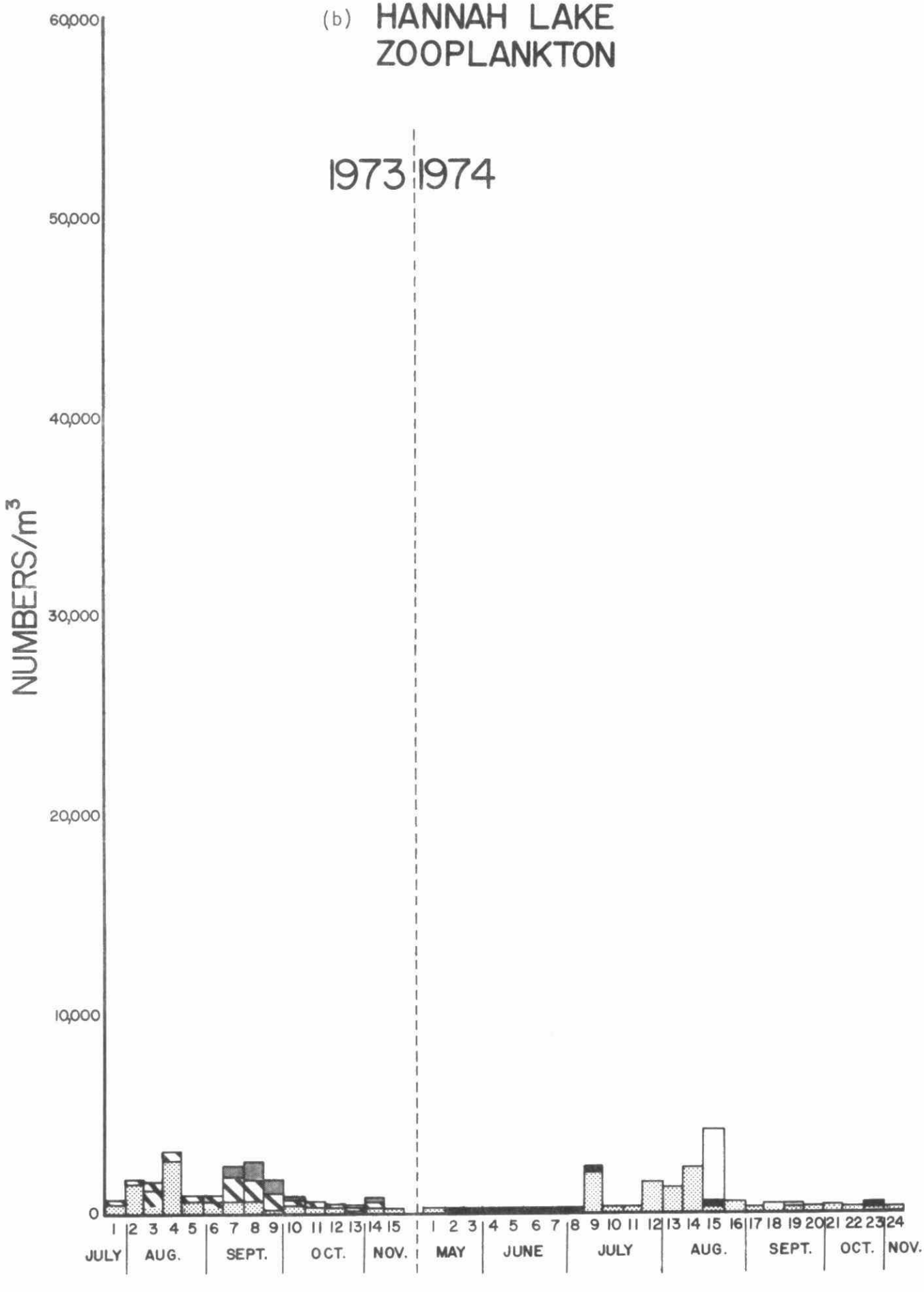
(b) Hannah Lake

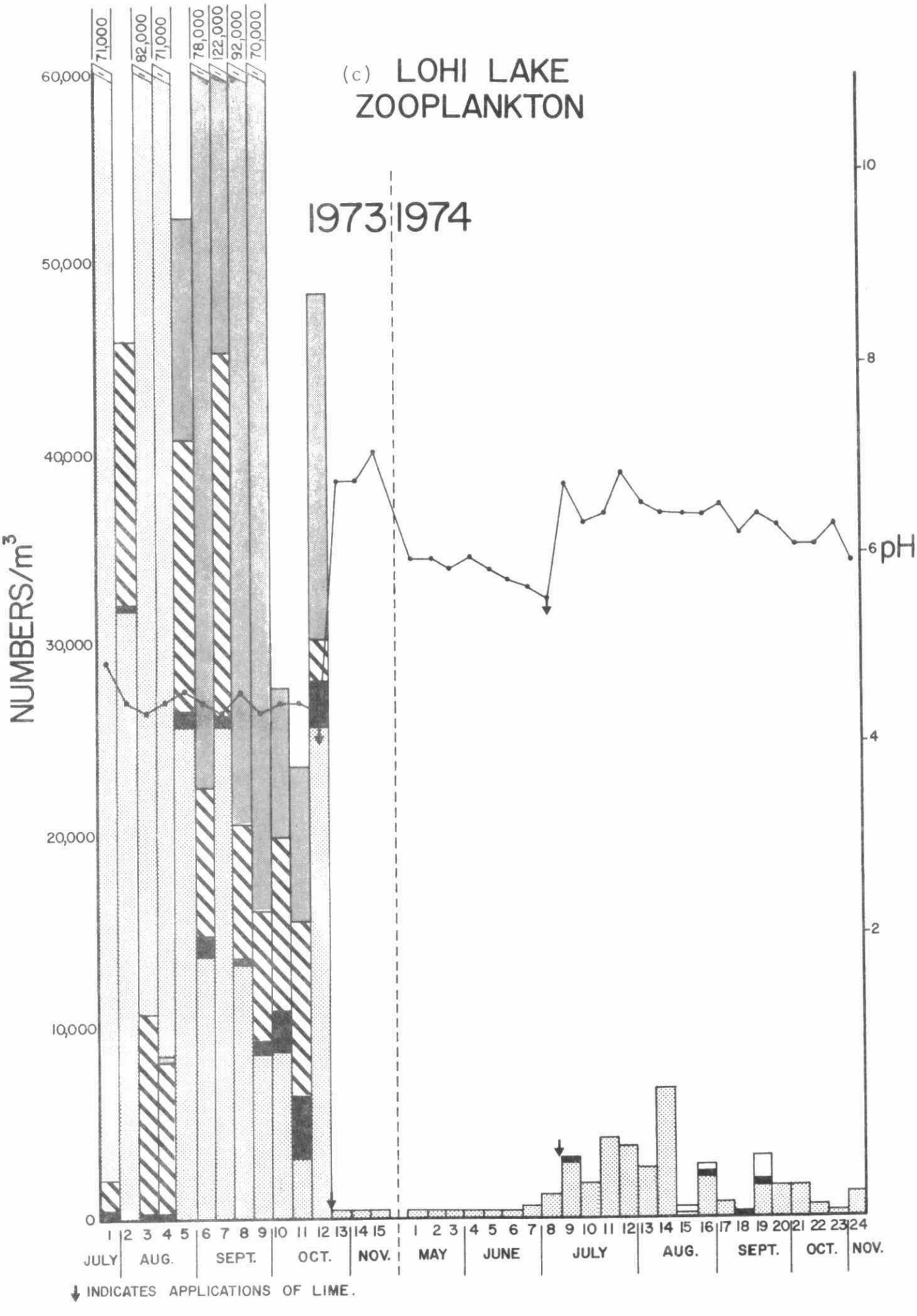
(c) Lohi Lake

(d) Clearwater Lake




(a) MIDDLE LAKE ZOOPLANKTON
1973 1974
74,000
60,000
50,000
40,000
30,000
20,000
10,000
0
NUMBERS/m3
10
8
6
4
2
pH
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 1 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
JULY AUG. SEPT. OCT. NOV. MAY JUNE JULY AUG. SEPT. OCT. NOV.
↓ INDICATES APPLICATIONS OF LIME.


(b) HANNAH LAKE
ZOOPLANKTON
1973 1974
NUMBERS/m3
60,000
50,000
40,000
30,000
20,000
10,000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
JULY AUG. SEPT. OCT. NOV.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
MAY JUNE JULY AUG. SEPT. OCT. NOV.


(c) LOHI LAKE
ZOOPLANKTON
1973 1974
71,000
82,000
71,000
78,000
122,000
92,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
NUMBERS/m3
10
8
6
4
2
pH
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
JULY AUG. SEPT. OCT. NOV.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
MAY JUNE JULY AUG. SEPT. OCT. NOV.
INDICATES APPLICATIONS OF LIME.

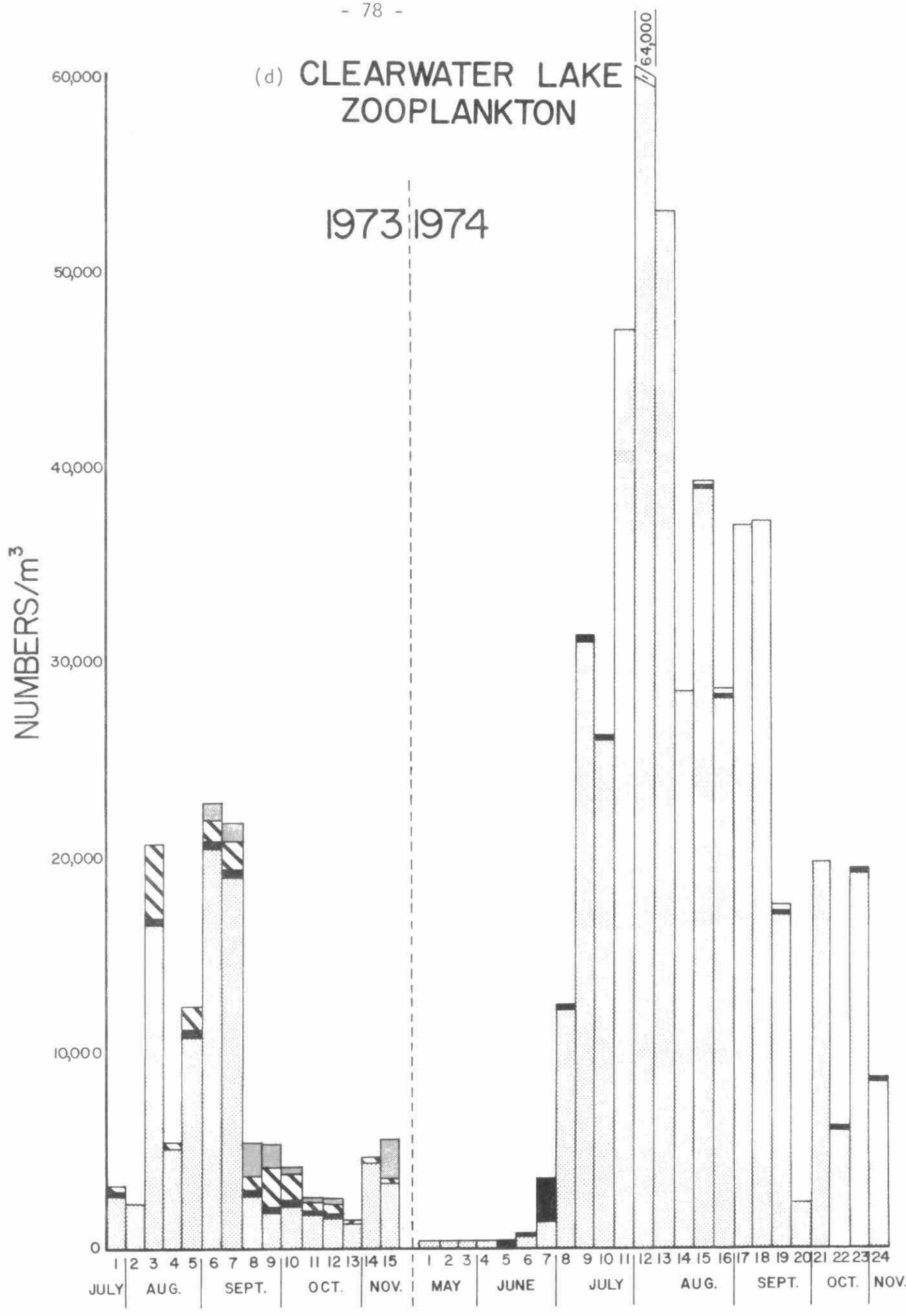
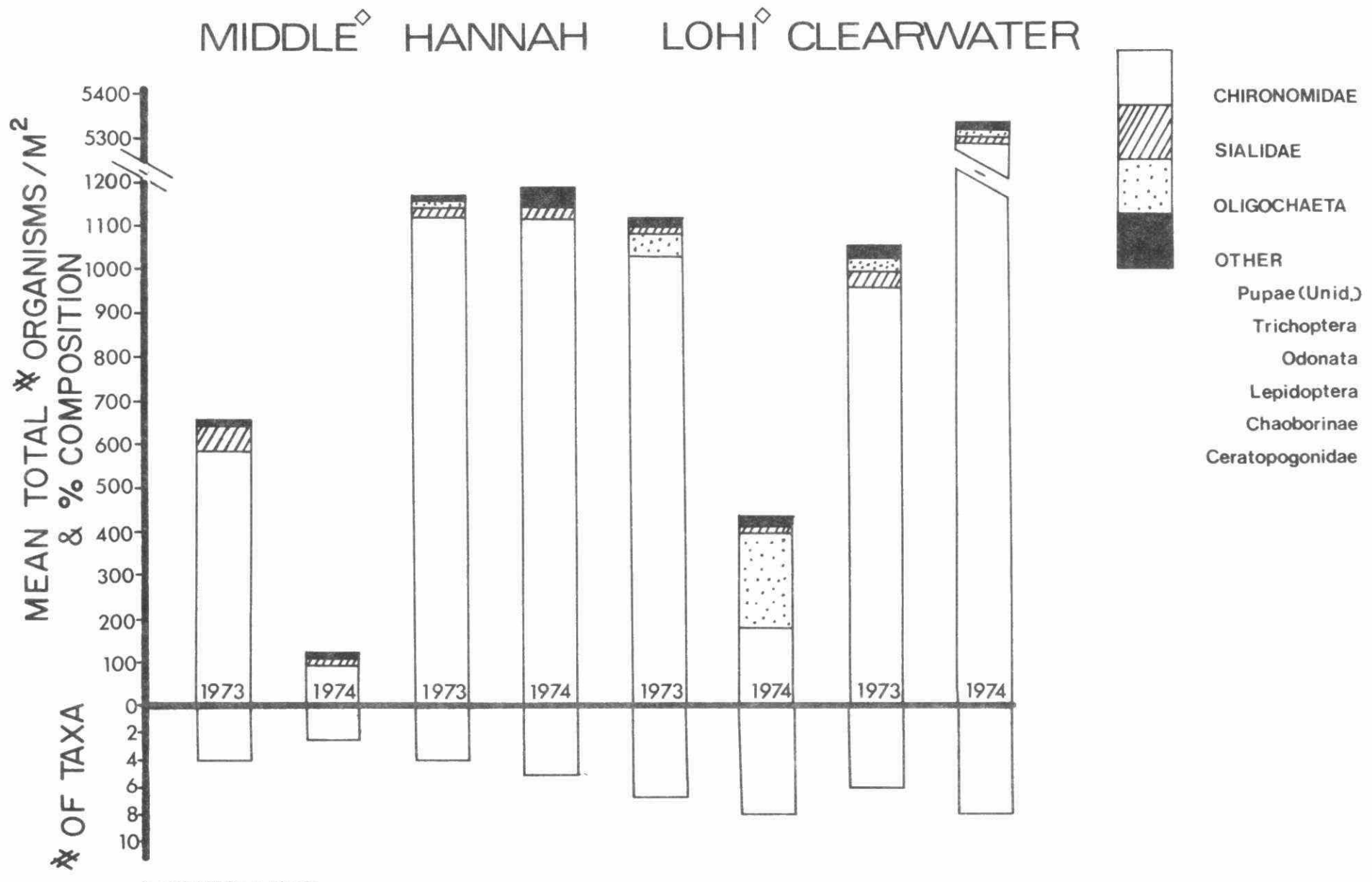

(d) CLEARWATER LAKE
ZOOPLANKTON
1973 1974
64,000
60,000
50,000
40,000
30,000
20,000
10,000
0
NUMBERS/m3
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
JULY AUG. SEPT. OCT. NOV.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
MAY JUNE JULY AUG. SEPT. OCT. NOV.

Figure 23: Zoobenthic Standing Stock and Taxonomic Composition



observations on the biology of stressed systems (Odum 1971). Although liming decreased the number of zooplankton, populations are expected to come back as a sufficient food source seems to be present.

(d) Benthic Macroinvertebrates

Benthic macroinvertebrates live in the lake sediments and at the mud-water interface. Commonly, aquatic insects form the bulk of the biomass or standing crop, usually in the larval stages. During the ice-free season, the larvae mature and emerge to fly, mate and lay eggs. Not all insect larvae remain in the sediments, nor do all crustaceans remain in the water column, hence the term "zoobenthos", which includes benthic macroinvertebrates plus other animals classically described as zooplankters. Generally, this group is important as a source of food for the young of many fish (Scott and Crossman, 1973).

In 1973 prior to treatment, the estimated number of organisms m^{-2} of lake sediment ranged from 654 to 1172 (Figure 23) in the study lakes with Chironomidae dominant in all lakes (> 85% of total numbers). These figures agree with those of Hamilton (1971), who reported numbers of 518 - 1642 m^{-2} with Chironomidae and Chaoborinae (midge larvae) dominant in lakes of intermediate size and depth in the ELA. Chaoborinae were found in Lohi and Clearwater lakes in very low numbers.

However, certain taxonomic groups were notably missing in the study lakes suggesting stress conditions (Mollusca, Insecta:Ephemeroptera).

Hagen and Langland (1973) reported acidic Norwegian lakes dominated by chironomid larvae, but lacking molluscs (snails and clams), mayflies (Ephemeroptera) and phantom midge (Chaoborinae). Estimated abundance was reported as 361 individuals m^{-2}. Grahn, Hultberg, and Landner (1974) found similar results in acidic Swedish lakes except that the Megalopteran (Insecta) *Sialis* formed the bulk of the biomass. In all study lakes, *Sialis* was common but not numerically dominant, agreeing with observations of tolerance to acidic water conditions (MacKenthun, 1969; Nichols and Bulow, 1973; and Warner, 1971).

Kwiatkowski (1974) examined six lakes near Killarney Provincial Park, 65 km southwest of Sudbury and postulated that below pH 5.0, phytoplankton, zooplankton and zoobenthos diversity decreased significantly. Ruth and Roy Lake (pH 4.3) had a zoobenthic species composition essentially the same as the study lakes except *Sialis* was not found.

Johnson and Owen (1966) examined rivers and lakes near Sudbury that were affected by local industrial wastes. Meatbird and Moose Lakes (pH < 4.5) had low numbers of zoobenthos dominated by midge. Moose Lake has since been treated with mechanically mixed crushed limestone but the effect on zoobenthos is not known (M.F.P. Michalski pers. comm.). Johnson and Owen (1966) also reported Norway Lake (pH 3.2) to be devoid of benthic macroinvertebrates.

Other organisms found in the study lakes were dragonflies (Odonata: Libellulidae), damselflies (Odonata:Coenagrionidae), aquatic moths (Lepidoptera: Pyralididae), aquatic worms (Oligochaeta) and caddisfly (Trichoptera:Psychomyiidae). Only the Oligochaeta assumed some numerical importance, and only in Lohi Lake. The other organisms were considered facultative and generally tolerant of stress conditions (Weber, 1973).

In 1974, the zoobenthos was examined for treatment effects. Based on Bowling and Busbee's (1964) liming of Georgia farm ponds, it was expected that the zoobenthic standing crop would increase in the first year after liming. However, total numbers of organisms m^{-2} decreased in both treated lakes, whereas they remained similar or increased in the control lakes (Figure 23, Appendix H). It is possible that the sudden change in lake pH detrimentally affected emergence and subsequently reduced the numbers of eggs laid, hence the drop in the succeeding year's population. Bell (1971) examined the effect of chronic exposure to low pH on 10 species of aquatic insects (none midge) and found them to be very sensitive to pH change during the emergence period. Vulnerability to pH change may also apply to moulting between larval instars.

The increase in numbers m^{-2} in 1974 in Clearwater Lake probably reflects the varied dates of sampling (see Appendix H). Hilsenhoff and Narf (1968) found *Chironomus plumosus* to have two peak emergence periods in Wisconsin lakes: early May, and July to September. Clearwater Lake was sampled in October 1974 after emergence, egg-laying and hatching of overwintering larvae had occurred. The 1974 value is thought to be a more accurate estimate. This is further supported by Hannah Lake which was sampled at a similar time each year, and showed no change in total numbers m^{-2}. These results imply that numbers in the treated lakes were underestimated in both years, but it is not known how significant this is.

All lakes except Middle had increased numbers of taxa in 1974, probably due to the larger dredge and increased sampling effort employed. The decrease in Middle was due to the absence of damselflies (only one was found

in 1973). This was not considered significant since damselflies are mostly facultative and not generally indicative of specific water conditions (Weber, 1973).

It should be noted that in 1974 on Middle Lake, the Eckman dredge was manually operated in varying weather conditions by relatively inexperiences staff. It is possible that many surface-dwelling organisms (midge in particular) were lost during sampling (Burton and Flannagan, 1973). Field notes indicated that dredge penetration into the sediments rarely exceeded 10 cm. Edmondson (1971) reported that 90% of xoobenthic populations are found up to 20 cm into the sediments and recommended that samples should extend to this depth.

Chironomidae continued to dominate the lakes in 1974 except in Lohi, where dominance was shared with Oligochaetes (44% and 47% of total numbers respectively). The fourfold postreatment increase in Oligochaetes in Lohi suggests an intermediate recovery situation. Stockinger and Hays (1960) found Oligochaetes to be more abundant in a partially recovered strip-mine lake (pH 6.2) than in the totally recovered lake (pH 7.2). Oligochaetes were not found in Middle Lake prior to treatment and distribution mechanisms are not known definitively (Brinkhurst and Jamieson, 1971).

A subsample of midges from Middle and Lohi Lakes were identified (Table 19).

Table 19: Species of midge (Diptera:Chironomidae) found in treated lakes in 1974.

		Subfamily	Tribe
Lohi	*Procladius* cf. *culiciformis*	(Tanypodinae	- Macropelopiini)*
	Protanypus sp. B †	(Diamesinae	- Protanypini)*
Middle	*Procladius* cf. *culiciformis*		
	Paracladopelma cf. *obscura* type	(Chironominae	- Chironomini)*
	Glyptotendipes (Phytotendipes)	"	"
	Chironomus thummi type ϕ	"	"

† Saether 1975 in press (Journal of the Fisheries Research Board Canada)
ϕ most likely *Chironomus decorus* (Dr. O.A. Saether - pers. comm.)
* Hamilton, Saether and Oliver (1969)

None of these organisms correspond to the dominant midge species listed in Hamilton (1971). Saether (1974) describes *Protanypus* and *Paracladopelma* as preferring profundal oligotrophic waters, and *Chironomus decorus* as being

commonly found in meso to eutrophic conditions. Data for 1973 and the control lakes 1974 was not available in time for publication.

In summary, the decline in zoobenthos in the first year after treatment is probably due to an interruption of the life cycle of the dominant organism, midge (Chironomidae), caused by a sudden change in pH. Since bacterial and phytoplankton levels are higher after treatment, a sufficient food source exists for the recovery of the zoobenthic population in future years.

(e) Fish

Although concrete evidence is unavailable, local residents report historic fisheries in all study lakes. No consensus on the species present was reached. In 1972, extensive trapping (Table 8) failed to catch any fish.

Increased acidity in lake waters has been reported as the agent responsible for declining salmonid fisheries in Norway and Sweden (Jensen and Snekvik, 1972; Almer, Dickson, Ekstrom, Hornstrom and Miller, 1974). Beamish and Harvey (1972) proposed that the fishery decline in acidic Lumsden Lake, 65 km southwest of Sudbury, was caused by adult spawning failure and egg and fry mortality in the low pH water. Overfishing was ruled out as the main cause because both sport and non-sport fish populations were affected. Craig and Baksi (1974) reported that reproduction in a laboratory population of the American flagfish (*Jordonella floridae*) ceased below pH 5.0. A histological examination of flagfish gonads showed the pathological effects of chronic exposure to the acidic water (Craig, pers. comm.).

Although mature, acclimated individuals of some species (pike, perch) can survive at pH levels as low as 4.0 - 4.5 (Grahn, Hultberg and Landner, 1974), the acidic, soft water increases the toxicity of free CO_2 and heavy metals (Environmental Protection Agency, 1972; EIFAC, 1968). The high concentrations of copper and nickel in the study lakes have already been discussed.

Mount and Stephan (1969) showed that the fathead minnow (*Pimephales promelas*) reproduced successfully in soft waters (30 mg l^{-1} $CaCO_3$) with a free copper concentration below 0.018 mg l^{-1}. McKim and Benoit (1971) examined long-term (chronic) effects of free copper on brook trout (*Salvelinus fontinalis*) in soft water (45 mg l^{-1} $CaCO_3$, pH of 7.5). They reported that adults would survive at or below 0.023 mg l^{-1} Cu but that eggs and juveniles would not

survive at levels above 0.0095 mg l^{-1}. Free copper levels in Middle and Lohi Lakes were 0.040 mg l^{-1} and 0.023 mg l^{-1} respectively in May 1974 (48 and 25 mg l^{-1} $CaCO_3$ respectively).

Pickering and Henderson (1966) reported 96 hr. TL_m for fathead minnows (Median Tolerance Limit, or the concentration at which 50% of the minnows die in 96 hr.) as 5.18 mg l^{-1} total Ni in soft water (20 mg l^{-1} $CaCO_3$). They estimated safe chronic exposure concentrations for fathead minnows as 0.100 mg l^{-1} nickel in soft water. Middle and Lohi lakes had total nickel concentrations of 0.57 mg l^{-1} and 0.27 mg l^{-1} respectively as of January 1975.

Although the liming process resulted in a reduction of copper and nickel concentrations, Figures 12 and 13 show that levels are rising to former values and may have exceeded chronic toxicity levels already. On-site toxicity work is planned for 1975 to answer this question.

4. Tube Fertilization

The tube enclosure studies were initiated on Clearwater and Lohi lakes but a storm in the sixth week destroyed the Clearwater set-up. Clearwater results are subsequently not included or discussed. Interpretation of the Lohi tube data is also complicated because the tubes had a poor seal with the sediments due to wave action and some were slightly torn.

a) Physical and Chemical Parameters

The temperature and oxygen profiles of the tubes were identical to the open water profiles. Tube mean Secchi disc values were slightly lower (ranging from 3.7 - 4.2 m) than lake values (mean of 4.6 m) suggesting reduced light penetration.

Chemical parameters (summarized in Appendix I) show there to be little difference between tubes or between tubes and open water with respect to major ions, minor ions and heavy metals.

b) Biological Parameters

The interpretation of biological data taken in enclosed water columns is difficult at best. Lund (1972) reported that small enclosures did not maintain the same phytoplankton populations as found in the open water. Jorden and Bender (1973) found enclosures to affect the species composition

of phytoplankton as well as reduce ^{14}C productivity. They attributed differences in enclosure and open water results to several factors: alteration in the quantity and quality of light; reduced water turbulence in the tubes resulting in reduced nutrient availability to organisms; bacterial and periphyton growth on vessel walls resulting in altered solute exchange; and accumulation of toxic metabolic wastes due to enclosure. Stoermer, Schelske and Feldt (1971) attributed the observed crash in phytoplankton populations in enclosed vessels to the accumulation of inhibitory substances secreted by blue-green algae. Jorden and Bender (1973) concluded that containment effects limit the precision of extrapolating enclosure fertilization results to a whole lake basis but do not negate the trends.

Microbiological data for Lohi Lake tended to show that counts in the tubes did not increase greatly with nutrient additions. Some of the observed increase was probably due to an enclosure effect as control tube counts were also higher than open water counts. However, the usual fall population decreases were not as marked in treated tube samples as in open lake water samples. Treated tube HPC:aciduric ratios (based on geometric mean values) were well above open water ratios but the same phenomenon occurred in control tubes and the effect is probably largely due to enclosure.

Although results were variable, several trends may be noted in the chlorophyll *a* data (Figure 24). There was no change in chlorophyll *a* levels in either the control or nitrogen-added tubes over the experimental period and levels approximated those in the open water. Concentrations in the tubes with phosphorus added increased to a maximum of 17.5 $\mu g\ l^{-1}$ and the tubes with sewage added showed a maximum of 21 $\mu g\ l^{-1}$ chl *a*. These results suggest that phosphorus is the element in shortest supply but that addition of a combination of nutrients (P, N, C, micronutrients as found in sewage) increases the phytoplankton standing crop to the greatest extent. However, the interpretation is tenuous as the extensive periphyton growth observed on the tube walls was not sampled.

Zooplankton numbers were higher in the enclosures than in the open water (Figure 25, Appendix J) with the sewage-added tubes showing the greatest numbers. However, in no case did zooplankton levels reach pre-treatment Lohi Lake values indicating that although fertilization may enhance recovery, other factors besides lack of food were responsible for the low post-treatment numbers observed in the open water. The cladoceran

Figure 24: Acidified Chlorophyll a and Cumulative Nutrient Additions to Lohi Lake Tube Enclosures 1974.

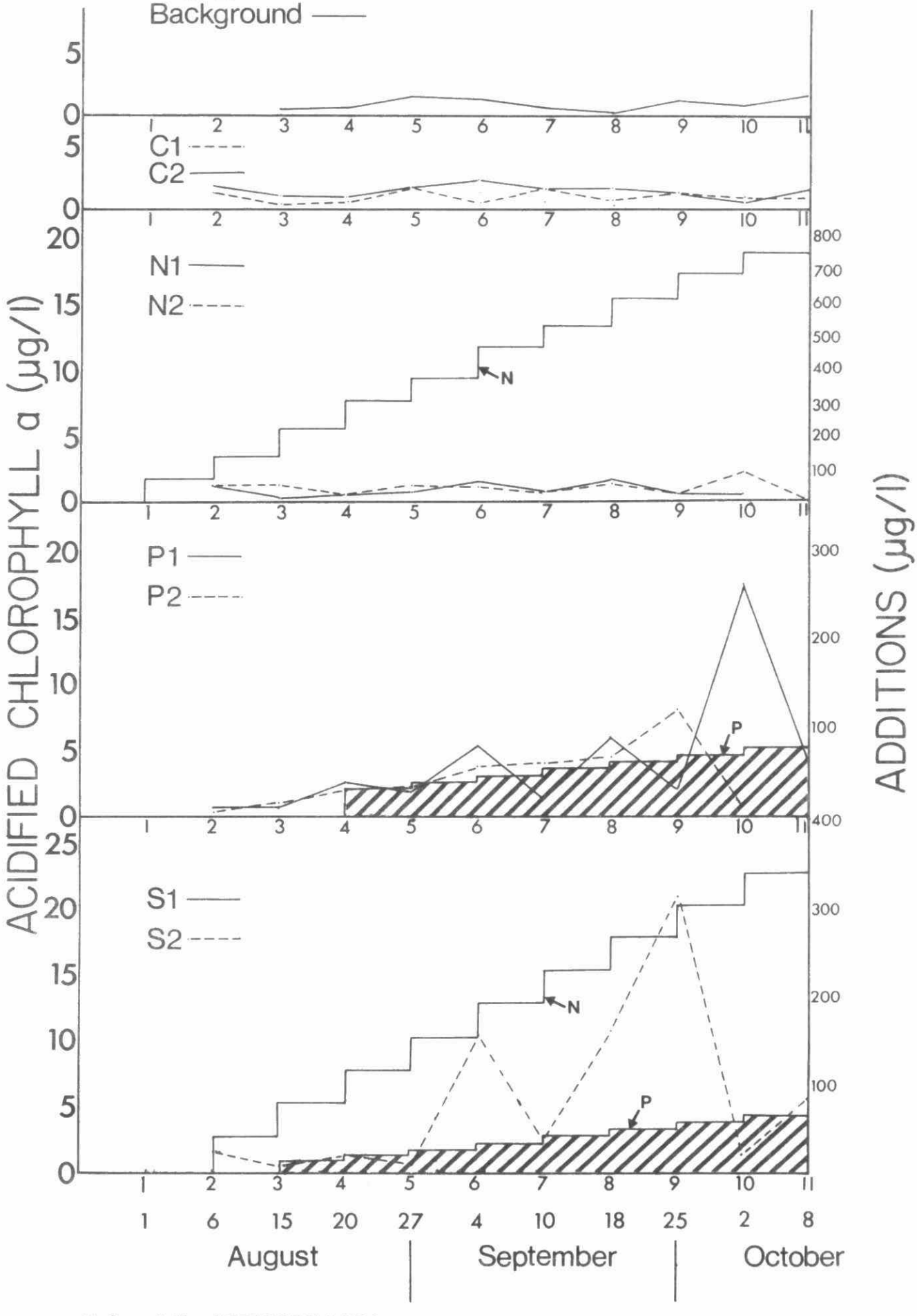


Figure 25: Zooplankton Standing Stock and Taxonomic Composition in Lohi Lake Tube Enclosures 1974.

Chydorus sphaericus was the major zooplankter in all tubes with *Ceriodaphnia megalops* and *Cyclops vernalis* usually co-dominant. The dominance of *Chydorus sphaericus* may be indicative of the artificial littoral environment created by the enclosures as this species is known to favour near-shore waters (Pennak, 1953).

In conclusion, the tube experiments showed that fertilization can act to increase the standing stock of bacteria, phytoplankton and zooplankton in a limed lake without affecting the major ion, minor ion or heavy metal levels. It may thus be a useful tool to speed the biological recovery of the treated lakes. A combination of nutrients (sewage) seemed to produce the greatest response.

5. Liming as a Means of Improving Water Quality

Liming has proven to be a simple, relatively inexpensive tool to offset acidic lake conditions and re-establish a weak buffer system in a controlled and predictable fashion. The pH of the sediments in the treated lakes has also increased and approximately 40% of the pre-treatment lime demand has been satisfied (as of summer 1974). The technique significantly reduced heavy metal levels in the water column, probably by a precipitation mechanism, and consequently increases in the sediment heavy metal levels were noted. Temperature and oxygen profiles were not affected, nor were minor ion concentrations. It is possible that total phosphorus and Kjeldahl nitrogen levels decreased due to precipitation by lime but levels were close to detection limit and the trend was inconclusive.

Treatment with $CaCO_3$ (in addition to $Ca(OH)_2$) seems to provide a carbonate reservoir and thus maintain a more stable buffer system. The lake treated with carbonate (Middle) continues to maintain a stable, near neutral pH 1½ years after treatment (pH = 6.5, March 1975), whereas Lohi Lake (only Ca(OH) added) dropped to pH 5.7 the summer following treatment. Although Lohi received a second lime addition in July 1974 to offset its acidic condition, the lake was again down to 5.6 as of March 1975. Heavy metal levels decreased to a greater extent in carbonate-treated Middle Lake and remained lower. Their gradual increase in post-treatment Lohi Lake is probably due to the concurrent decrease in pH.

The microbial populations generally showed a rapid positive response to liming in both treated lakes, with the numbers of aerobic heterotrophs, sulphate reducers and non-acidophilic sulphur oxidizers increasing. Sediment populations remained relatively constant. Phytoplankton standing crop increased in all lakes in 1974, but the increase was greater in the treated than control lakes (five-fold as opposed to a doubling of a.s.u. ml^{-1}). A shift in species dominance to Chrysophyceae occurred, although interpretation is confused by the similar trend in the control lakes. Zooplankton numbers declined in the treated lakes by an order of magnitude. This is probably due to a lethally rapid pH change at the time the dominant zooplankter, Cladocera, was laying overwintering eggs, hence reducing the spring 1974 cohort. Similarly, the zoobenthic population decline in the treated lakes is attributed to an interruption of the life cycle of the dominant organism, midge, caused by the sudden pH increase. However, as a sufficient food source seems to exist (phytoplankton, bacteria), it is expected that numbers of zooplankton and zoobenthos will increase.

In conclusion, liming has improved the chemical water quality of the lakes with carbonate plus hydroxide treatment maintaining a more stable system. The increased standing stock of the microbial and phytoplanktonic trophic levels is expected to be followed by increases in zooplankton and soobenthos populations. Evidence from the tube enclosure studies indicates that the recovery may be speeded by fertilization.

6. Future Studies

Having satisfied the primary objective of neutralizing an acidic lake, several further studies are planned for 1975.

Data indicate that a combination of carbonate plus hydroxide treatment provides a more stable buffer system. As Lohi Lake has shown a decline in pH with hydroxide only, it will be treated with hydroxide plus carbonate. Hannah Lake will also be treated to further assess the technique and as a control for fertilization, leaving Clearwater as a control lake. Chemical and biological monitoring will continue on the four lakes discussed in this study.

It is not known definitely whether sediment demand or lake flushing with acidic input is the main cause for the drop in pH observed in Lohi Lake. To answer this question and obtain an estimate of the duration of treatment, hydrological and chemical budget work is planned for all lakes. Nutrient budgets will also be measured.

To further assess the feasibility of the treatment, two larger lakes (Nelson, 313 ha, and Joe, 182 ha) will be included in the study beginning this year.

They have a pH of approximately 5.5, low heavy metal levels and marginal fisheries. Background data will be gathered on both lakes this year and Nelson may be limed in the late summer.

As the tube enclosure studies indicated that fertilization may speed biological recovery of a treated lake, a whole-lake fertilization is planned for Middle Lake, raising phosphorus levels to those normally found in oligotrophic Shield lakes.

In co-operation with the Ministry of the Environment Toxicity Section on-site flow-through bioassays will be carried out on two of the study lakes to assess the suitability of the treated water for fish growth and survival. Concurrently, the Toxicity Section will examine effects of pH and copper on fish under laboratory conditions.

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APPENDICES

A. Preliminary Survey, Chemical and Physical Parameters of Ten Lakes near Sudbury (taken June 25-28, 1973).

B. Sampling Frequency 1973/1974.

C. Sampling Locations 1973/1974

D. Summary of Major/Minor Ions in Study Lakes 1973/1974

E. Mean Values for Heavy Metals in Study Lakes 1973/1974

F. Summary of Phytoplankton in Study Lakes 1973/1974.

G. Summary of Zooplankton in Study Lakes 1974/1974

H. Summary of Zoobenthos in Study Lakes 1973/1974

I. Mean Values of Chemical Parameters for Lohi Lake Enclosures

J. Zooplankton Counts for Lohi Lake Enclosures.

ppendix A: Preliminary survey, chemical and physical parameters of ten lakes near Sudbury (taken June 25-28, 1973).

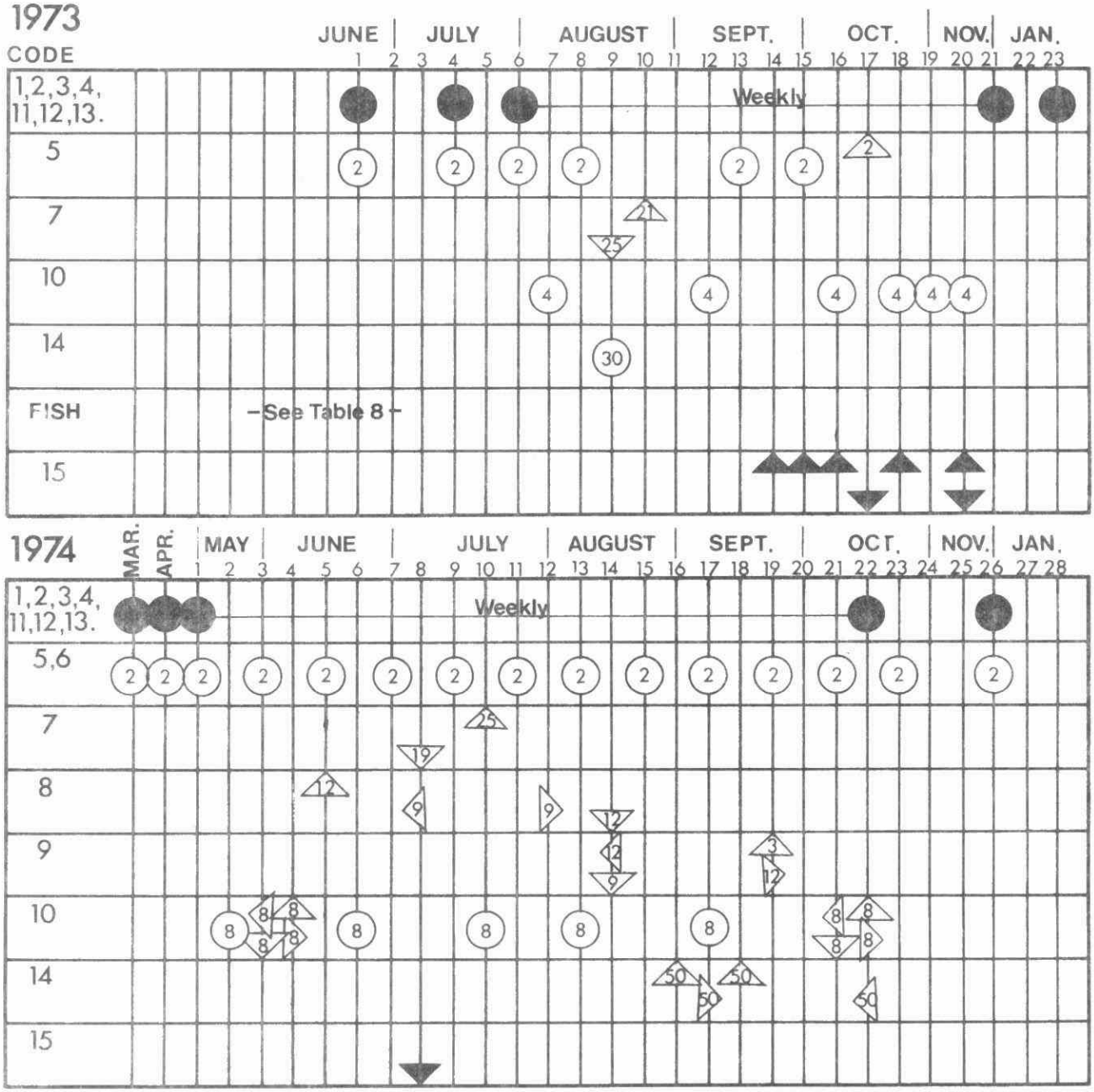
		Maximum Depth (m)	Secchi Disc (m)	pH	Alkalinity (mg/l)	Hardness (mg/l)	Sulphate (mg/l)	Conductivity (μmhos/cm^3)	Chlorophyll (μg/l)
Little Round Lake	s	4.0	3.0	6.1	7.0	29	21	74	2.1
	b			6.3	7.0	30	21	75	
Bass Lake	s	12.0	4.0	6.3	4.0	25	22	66	0.9
	b			6.1	7.0	26	20	67	
Hannah Lake	s	7.8	7.6	4.9	0.0	43	55	161	0.6
	b			4.6	0.0	43	55	162	
Middle Lake	s	12.0	9.0	4.5	0.0	36	42	131	0.3
	b			4.6	0.0	38	41	129	
Clearwater Lake	s	20.3	6.8	4.8	3.0	27	26	88	0.3
	b			4.5	0.0	28	26	87	
Lohi Lake	s	16.5	7.7	4.6	0.0	24	26	87	0.5
	b			4.8	0.1	24	25	78	
Tilton Lake	s	10.5	6.0	5.4	2.0	22	20	64	0.3
	b			6.8	9.0	31	21	72	
Lake C-1	s	3.5	2.8	6.6	3.0	22	22	63	1.2
	b			6.6	4.0	23	22	63	
Lake C-2	s	20.8	9.0	6.9	2	24	23	71	0.5
	b			6.5	3	23	22	64	
Lake C-3	s	9.8	4.2	6.7	4	21	18	53	1.5
	b			6.5	7	21	18	57	

s - Represents sample taken at 1m of depth (IMBS)

b - Represents sample taken 1m off bottom (IMAB)

Appendix B: Sampling Frequency for Reclamation Lakes

Code	Parameter
1	pH, conductivity, alkalinity, hardness, Ca, Mg, CO_2.
2	turbidity (1974), suspended solids (1974), Cl, Na, K, SO_4.
3	temperature, depth, secchi, dissolved oxygen.
4	silica, ammonia, nitrite, nitrate, Kjeldahl nitrogen, total phosphorus, dissolved orthophosphate.
5	Ni, Zn, Cu, Fe, Mn (water)
6	Al, As, Co, Cd (water)
7	sediment cores: loss on ignition, Kjeldahl nitrogen, total phosphorus, pH, lime demand, Cu, Ni, Zn, Mn, Fe, Ca, Mg, Cr.
8	sediment profiles: Ni, Cu, Fe, Zn, Cr, Ca, Pb, pH.
9	sulphide (water)
10	microbiological
11	^{14}C, inorganic, organic and total carbons
12	phytoplankton, chlorophyll a
13	zooplankton
14	benthos
15	liming
●	refers to week in which code parameters were sampled in all lakes.
(2)	internal number refers to number of samples taken per lake in all lakes.
△	specific sampling on Middle Lake
▷	specific sampling on Hannah Lake
▽	specific sampling on Lohi Lake
◁	specific sampling on Clearwater Lake
19	internal number refers to number of samples taken per indicated lake.


1973
CODE
JUNE
JULY
AUGUST
SEPT.
OCT.
NOV.
JAN.
1,2,3,4, 11,12,13.
Weekly
5
7
10
14
FISH
–See Table 8–
15
1974
MAR.
APR.
MAY
JUNE
JULY
AUGUST
SEPT.
OCT.
NOV.
JAN.
1,2,3,4, 11,12,13.
Weekly
5,6
7
8
9
10
14
15
1974 TUBES
1,2,3,4, 12.
Weekly
5,6
13
10

LEGEND

A MAIN SAMPLING STATION - Physical Parameters
Biological - (Zooplankton, Phytoplankton, Chlorophyll, ^{14}C)
Chemical Parameters
Microbiology (Station #1)
Sediment Trap Station

B MICROBIOLOGY - (Station #2) - Approximate Location

NUMBERS: ① ② ③ ④

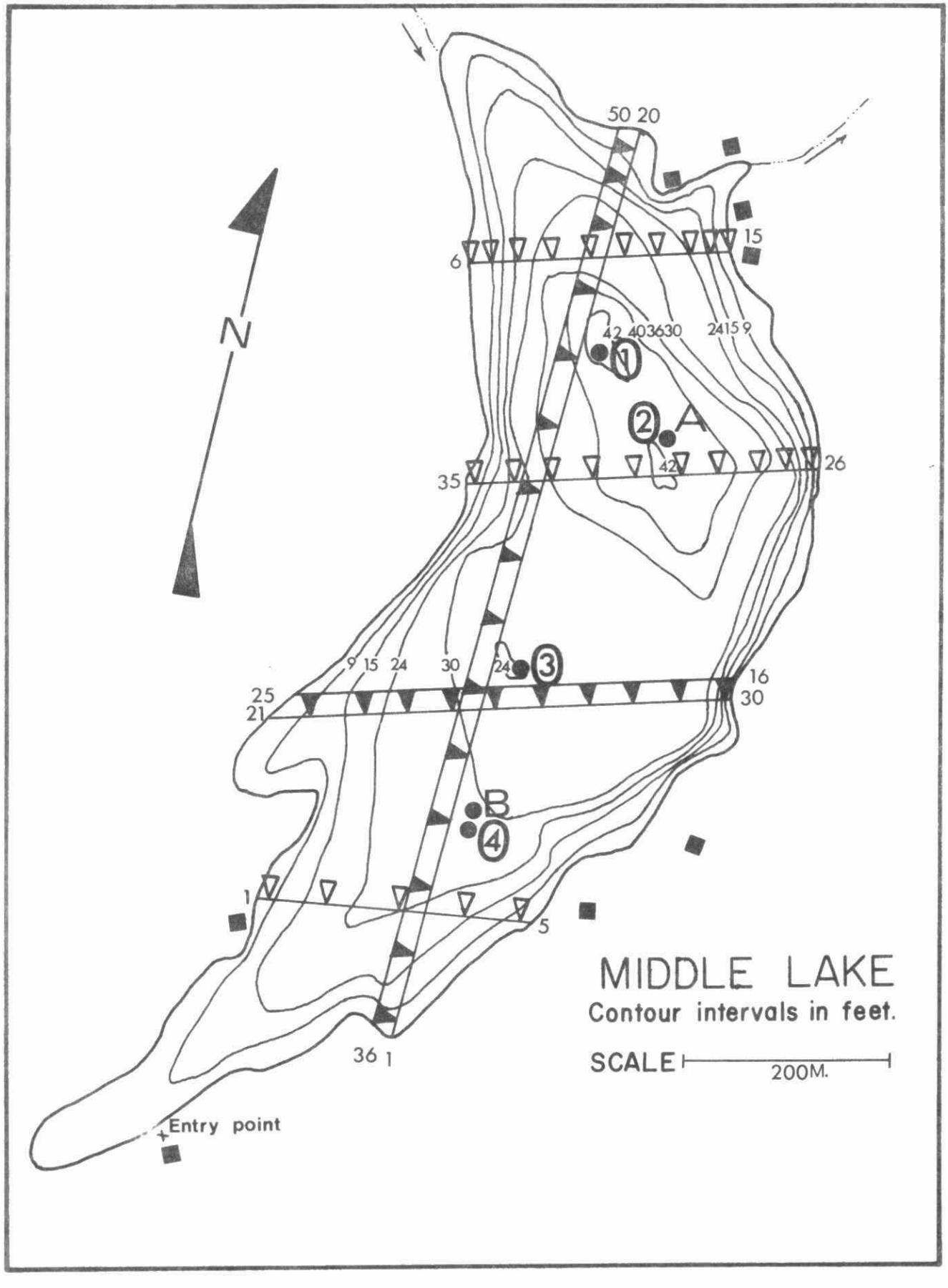
METALS: Sediment Profile Study Station Locations

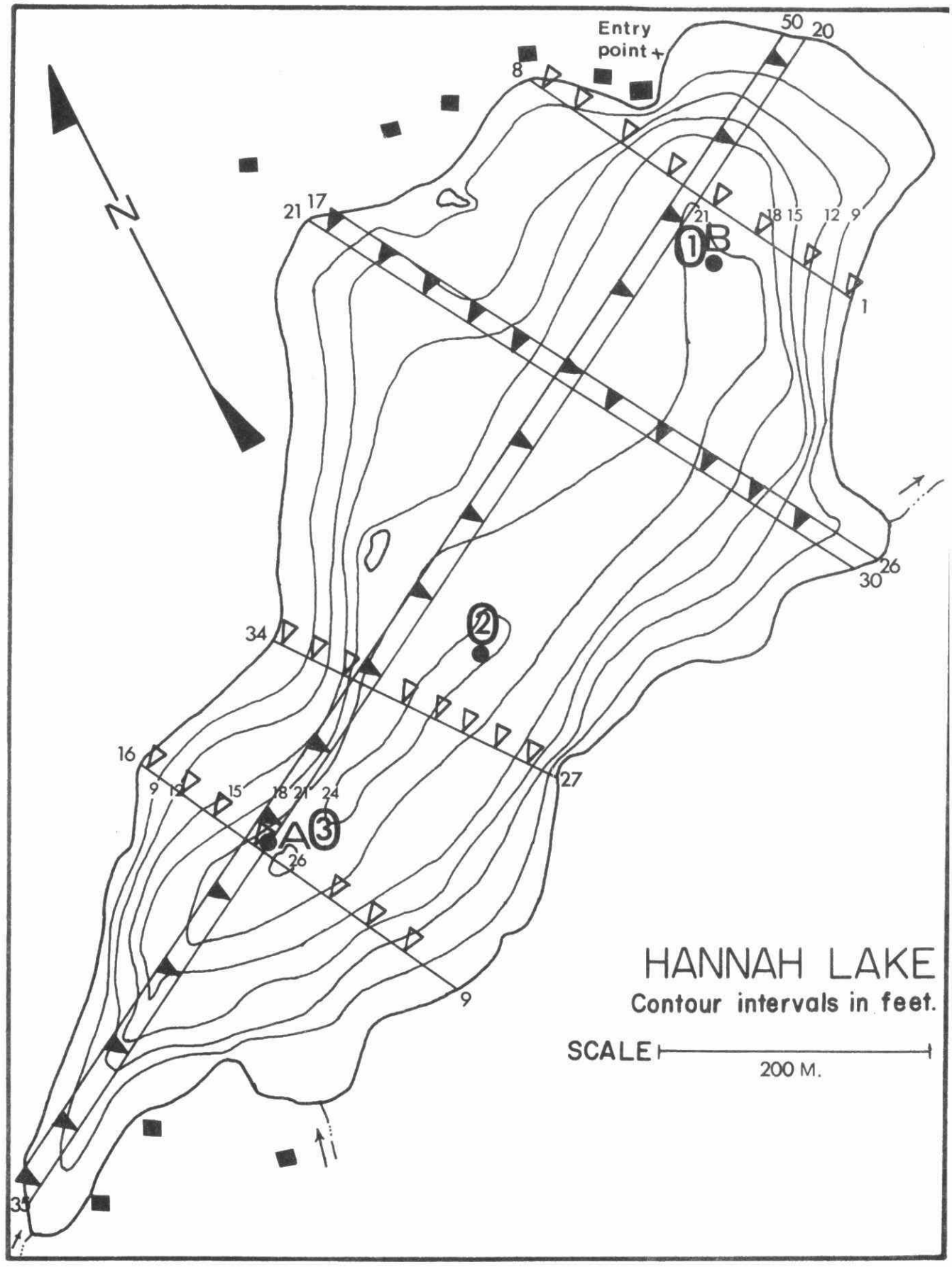
BENTHOS SAMPLING:

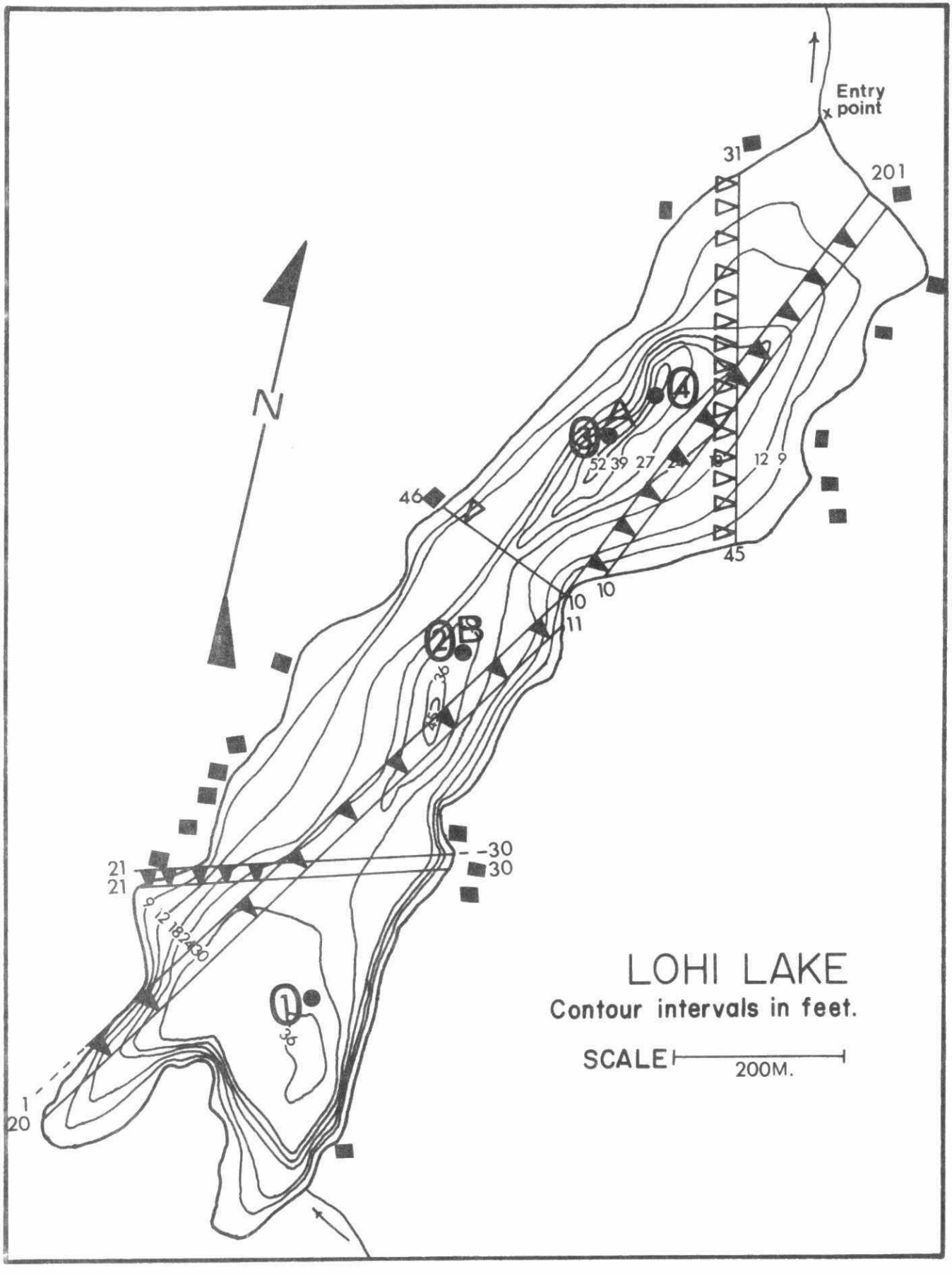
▽ ▽ ▽ 1974 Benthos Stations (New)

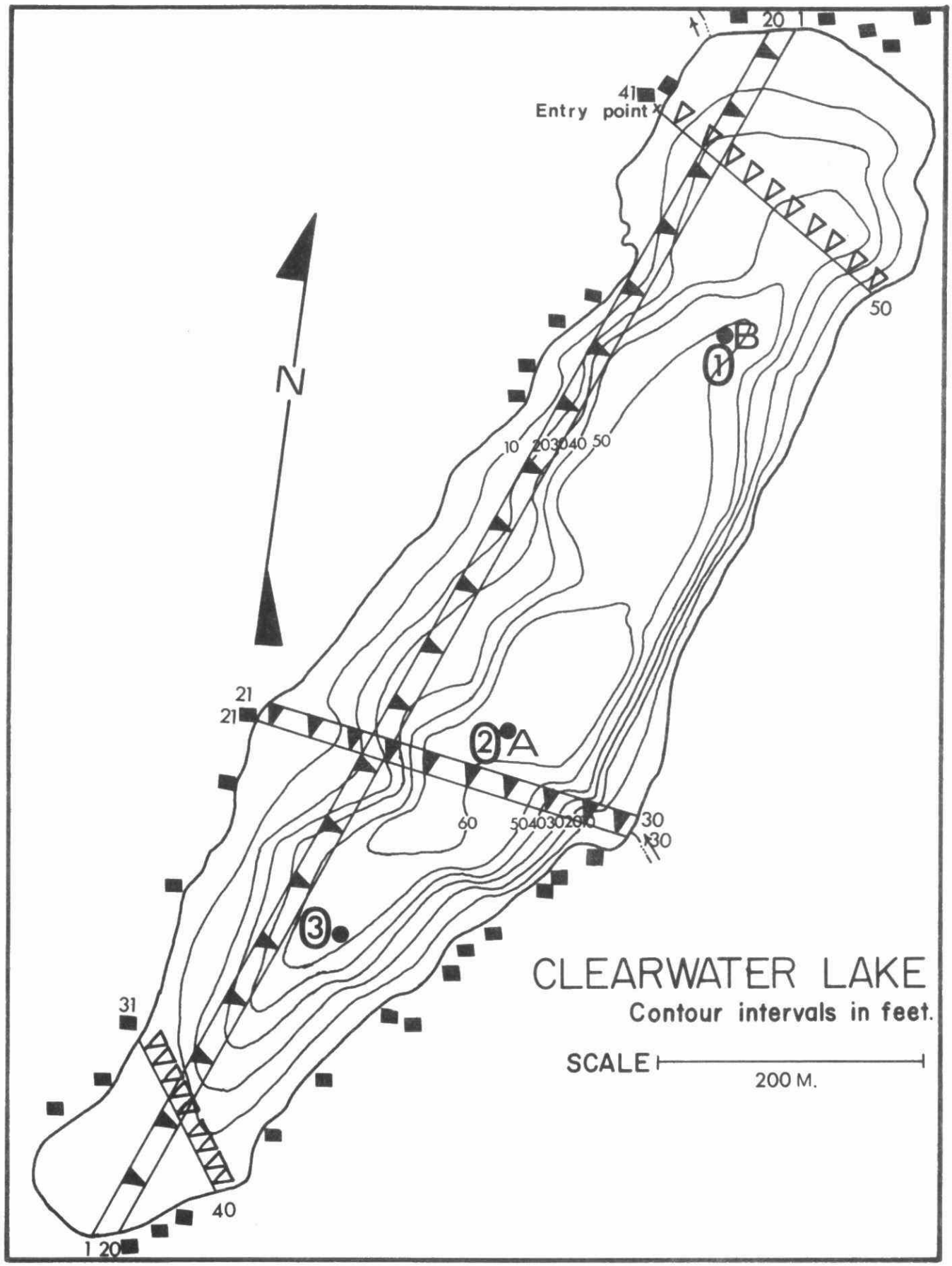
▼ ▼ ▼ Benthos Stations Common To 1973 & 1974

■ Approximate Location Of Cottages.


N
50 20
6
15
42 40 36 30
24 15 9
1
2
A
42
35
26
9 15 24 30 24
3
25
21
16
30
B
4
1
5
36 1
Entry point
MIDDLE LAKE
Contour intervals in feet.
SCALE
200M.


Entry
point
N
50
20
8
21
17
21
18
15
12
9
1
B
1
30
26
34
2
16
9
12
15
18
21
24
A
3
26
27
9
35
HANNAH LAKE
Contour intervals in feet.
SCALE
200 M.


Entry
x point
31
201
N
52 39 27
12 9
46
45
10
10
11
21
21
-30
30
9 12 18 24 30
36
1
20
LOHI LAKE
Contour intervals in feet.
SCALE
200M.


20
1
41
Entry point
50
N
B
1
10 20 30 40 50
21
21
2
A
60 50 40 30 20 10
30
30
3
CLEARWATER LAKE
Contour intervals in feet.
SCALE
200 M.
31
40
1 20

Summary of Major/Minor Ions in Study Lakes (mg l^{-1} unless specified)

Middle Lake (MBS)

		pH	Alkalinity	Hardness	Conductivity[1]	Ca	Mg	Cl	Na	K	SO_4	Composite Si
1973	$\bar{y}$	4.5	.4	39	135	9.8	5.0	-	2.4	2.0	44.5	2.8
Pretreatment	n	10	5	10	9	9	9	-	8	8	10	9
	s	.28	.8	4.6	10.9	.4	.9	-	.5	.5	2.2	.1
1973	$\bar{y}$	6.6	4.5	45	124	14.8	3.0	-	2.3	1.8	46.0	3.0
Postreatment	n	7	2	6	6	4	3	-	3	3	5	6
	s	.99	.7	2.6	2.4	1.7	-	-	.6	.2	1.2	.1
1974	$\bar{y}$	7.0	6.9	46	127	14.2	2.6	1.5	2.4	1.7	42.2	3.3
	n	23	21	23	22	22	23	23	23	23	22	23
	s	.16	1.4	1.4	2.0	.4	.4	.3	.3	.3	2.4	.3

Middle Lake (MAB)

1973	$\bar{y}$	4.5	.6	38	134	9.6	4.9	-	2.1	1.8	44.8	-
Pretreatment	n	10	5	10	9	8	8	-	8	8	10	-
	s	.17	1.2	2.9	11.5	.5	1.1	-	.4	.4	2.0	-
1973	$\bar{y}$	6.8	5.5	45	124	14.8	4.0	-	2.3	1.7	46.2	-
Postreatment	n	7	2	6	6	4	3	-	3	3	5	-
	s	1.3	1.3	3.0	3.8	3.8	1.0	-	.6	.2	1.3	-
1974	$\bar{y}$	6.6	8.7	47	128	14.4	2.4	1.4	2.4	1.7	41.0	-
	n	23	23	23	23	23	23	21	23	23	23	-
	s	.19	1.2	1.4	2.0	.5	.2	.2	.4	.3	1.3	-

$\bar{y}$ = mean value
n = number of samples
s = standard deviation

1. conductivity in µmohs cm^{-1}

Appendix D: Continued.

Hannah Lake (MBS)

		pH	Alkalinity	Hardness	Conductivity	Ca	Mg	Cl	Na	K	SO_4	Composite Si
1973	$\bar{y}$	4.5	.4	47	168	13.7	5.3	-	3.1	2.1	55.5	1.0
Pretreatment	n	11	5	11	10	10	10	-	9	9	11	10
	s	.2	.8	3.3	5.2	4.0	2.1	-	.6	.4	3.8	.1
1973	$\bar{y}$	4.4	-	45	167	12.0	4.0	-	3.0	1.8	58.0	1.2
Postreatment	n	4	-	4	4	2	2	-	2	2	4	4
	s	.2	-	1.7	4.1	-	1.4	-	-	.1	1.4	.1
1974	$\bar{y}$	4.3	0	43	166	11.4	3.6	2.6	3.5	2.1	58.8	1.1
	n	23	23	23	23	22	22	21	23	23	23	21
	s	.1	-	5.0	5.0	.5	.2	.5	.9	.6	10.7	.3

Hannah Lake (MAB)

1973	$\bar{y}$	4.4	.4	47	169	11.4	5.7	-	3.0	2.0	55.9	-
Pretreatment	n	11	5	11	10	10	10	-	9	9	11	-
	s	.1	.8	3.3	5.2	1.6	2.1	-	-	.4	3.1	-
1973	$\bar{y}$	4.3	-	45	170	12	5.0	-	3.0	1.8	58.5	-
Postreatment	n	3	-	3	3	1	1	-	2	2	4	-
	s	-	-	.6	2.7	-	-	-	-	.1	1.3	-
1974	$\bar{y}$	4.3	0	43	166	11.5	3.6	2.8	3.4	2.1	60.4	-
	n	23	23	23	23	23	22	20	23	23	22	-
	s	.1	-	1.3	4.9	.5	.2	.2	.3	.4	5.9	-

$\bar{y}$ = mean value
n = number of samples
s = standard deviation

Appendix D: Continued.

Lohi Lake (MBS)

		pH	Alkalinity	Hardness	Conductivity	Ca	Mg	Cl	Na	K	SO_4	Composite Si
1973	$\bar{y}$	4.4	.6	21	87	6.2	2.6	-	1.9	1.3	26.7	2.7
Pretreatment	n	14	5	14	14	11	11	-	11	11	14	13
	s	.1	.8	1.2	5.6	.4	1.0	-	.5	.4	1.3	.2
1973	$\bar{y}$	6.4	-	27	76	9.0	1.0	-	2.0	1.2	29.0	2.5
Postreatment	n	3	-	1	2	1	1	-	1	1	1	1
	s	.7	-	-	2.1	-	-	-	-	-	-	-
1974	$\bar{y}$	6.2	2.2	25	75	7.9	1.3	1.6	1.5	1.0	25.7	3.5
	n	23	23	23	23	23	22	21	23	23	23	23
	s	.4	.5	.8	.9	.3	.2	.3	.3	.2	1.5	.4

Lohi Lake (MAB)

1973	$\bar{y}$	4.9	2.6	21	79	6.0	2.5	-	1.8	1.2	25.4	-
Pretreatment	n	14	5	14	13	11	11	-	10	10	14	-
	s	.5	1.7	1.5	6.0	.9	.9	-	.6	.2	1.8	-
1973	$\bar{y}$	6.5	-	27	75	9.0	1.0	-	2.0	1.2	29.0	-
Postreatment	n	3	-	1	2	1	1	-	1	1	1	-
	s	.8	-	-	1.4	-	-	-	-	-	-	-
1974	$\bar{y}$	5.9	2.7	25	75	7.7	1.3	1.5	1.5	1.0	25.1	-
	n	22	23	23	23	23	22	21	23	23	23	-
	s	.1	.5	.8	1.1	.2	.2	.3	.3	.2	1.7	-

$\bar{y}$ = mean value
n = number of samples
s = standard deviation

Appendix D: Continued.

Clearwater Lake (MBS)

		pH	Alkalinity	Hardness	Conductivity	Ca	Mg	Cl	Na	K	SO_4	Composite Si
1973	$\bar{y}$	4.4	.6	21	91	6.2	2.4	-	1.6	1.3	27.7	4.0
Pretreatment	n	14	5	14	14	11	11	-	11	11	14	13
	s	.3	1.2	1.8	4.6	.4	1.1	-	.5	.4	1.1	1.3
1973	$\bar{y}$	-	-	-	-	-	-	-	-	-	-	-
Postreatment	n	-	-	-	-	-	-	-	-	-	-	-
	s	-	-	-	-	-	-	-	-	-	-	-
1974	$\bar{y}$	4.3	0	19	86	5.5	1.3	1.1	1.5	1.0	25.6	4.2
	n	22	23	23	23	22	23	21	23	23	23	23
	s	.1	0	1.5	2.7	.3	.4	.2	.3	.2	2.0	.4

Clearwater Lake (MAB)

1973	$\bar{y}$	4.4	.4	21	90	6.4	2.4	-	1.6	1.2	27.4	-
Pretreatment	n	14	5	14	14	11	11	-	11	11	14	-
	s	.1	.8	2.3	4.0	.5	.9	-	.5	.4	1.1	-
1973	$\bar{y}$	-	-	-	-	-	-	-	-	-	-	-
Postreatment	n	-	-	-	-	-	-	-	-	-	-	-
	s	-	-	-	-	-	-	-	-	-	-	-
1974	$\bar{y}$	4.3	0	19	86	5.5	1.2	1.1	1.5	1.0	26.4	-
	n	23	23	23	23	23	23	21	23	23	23	-
	s	.1	0	1.0	1.9	.2	.4	1.8	.3	.2	4.3	-

$\bar{y}$ = mean value
n = number of samples
s = standard deviation

Appendix E: Mean Values for Heavy Metals in Study Lakes (mg l^{-1})

Meter Below Surface

		Al	Cd	Co	Cu	Fe	Mn	Ni	Pb	Zn
1973	Hannah	-	-	-	-	-	-	-	-	.090
Pretreatment	Middle	-	-	-	.090	-	-	.280	-	-
(1 sample)	Clearwater	-	-	-	.090	.110	-	.250	-	-
	Lohi	-	-	-	.090	.090	-	.250	-	.030
1974										
(10-12	Hannah	1.15	.004	.034	1.12	.085	.344	1.85	.022	.122
samples)	Middle	.216	.005	.009	.068	.187	.151	.339	.007	.049
	Clearwater	.521	.001	.010	.194	.095	.312	.286	.009	.047
	Lohi	.149	.001	.007	.042	.050	.245	.192	.005	.030

Meter Above Bottom

1973	Hannah	-	-	-	1.06	.090	.396	1.58	-	.122
Pretreatment	Middle	-	-	-	.496	.135	.350	1.07	-	.089
(4-6 samples)	Clearwater	-	-	-	.148	.170	.324	.398	-	.048
	Lohi	-	-	-	.080	.492	.284	.245	-	.084
1973	Hannah	-	-	-	1.10	-	-	1.70	-	1.30
Postreatment	Middle	-	-	-	.240	.065	.287	.630	-	.045
(1-3 samples)	Clearwater	-	-	-	-	-	-	-	-	-
	Lohi	-	-	-	-	-	-	-	-	-
1974	Hannah	.444	.004	.034	1.13	.094	.341	1.87	.022	.200
(10-12	Middle	.201	.002	.009	.083	.099	.201	.373	.008	.030
samples)	Clearwater	.536	.011	.011	.184	.163	.306	.275	.008	.062
	Lohi	.169	.001	.008	.053	.063	.255	.213	.005	.031

APPENDIX F: Summary of Phytoplankton Standing Stocks

MIDDLE LAKE 1973	July 30	Aug. 8	Aug. 13	Aug. 20	Aug. 27	Sept. 5	Sept. 11	Sept. 18	Liming 25-26..	" Sept. 27 28...	" Oct. 1 3.....	" Oct. 9	" 17.... Oct. 18	Oct. 22 29-1...	Nov. 1	Nov. 5
Week	1	2	3	4	5	6	7	8		9	10	11	12	13	14	15
MYXOPHYCEAE																
Chroococcus										P						
CHRYSOPHYCEAE																
Dinobryon		1												2		
Unid Chrysophyte*		2	21	59	81			35							1	
" Chrysomonad		6	4	1	9		6	55		4	1	1	1†	5	3	2
" Flagellate	1	2						43								
" Green+		1			P		2							P	1	P
CHRYPTOPHYCEAE																
Cryptomonas	2	28	18	19	46	33	29	27		1	6	1				
Rhodomonas	1			P	1		2									
CHLOROPHYCEAE																
Cosmarium		1								4						
Chlamydomonas		P		P		1	2	22		6	4	1		1	P	
Oocystis							2			P	P	P				
Selenastrum						117	82									
Staurastrum										2						
DINOPHYCEAE																
Peridinium	28	20	11	13	10	81	105	48		28	4	2				3
EUGLENOPHYCEAE																
BACILLARIOPHYCEAE																
Cyclotella										1						
Cymbella										P						
Eunotia											1					
Nitzchia										P						
TOTALS	32	61	54	92	147	232	230	230		46	18	5	1	13	6	5

* Similar in appearance to Selenastrum (a Chlorophyte)
+ Similar in appearance to Mougeotia
† Fungal spores abundant.
..... Liming

APPENDIX F - Cont'd....

MIDDLE LAKE 1974	16 May	22 May	29 May	5 June	13 June	20 June	27 June	3 July	10 July	25 July	8 Aug.	22 Aug.	5 Sept.	18 Sept.	2 Oct.
Week	1	2	3	4	5	6	7	8	9	11	13	15	17	19	21
MYXOPHYCEAE															
Chroococcus		6													
Oscillatoria					2	3	3	2	5	5	5		3	13	
CHRYSOPHYCEAE															
Dinobryon					1	16	40	7	3	771	538	362	18	19	38
Kephyrion											21			9	20
Unid Chrysomonad	2						1040	1	1	8	408	722	387	217	327
CHRYPTOPHYCEAE															
Rhodomonas		1		1											
CHLOROPHYCEAE															
Ankistrodesmus											1				
Cosmarium											4		2		
DINOPHYCEAE															
EUGLENOPHYCEAE															
Euglena											1				
BACILLARIOPHYCEAE															
Achnanthes			1		1	1	7	5	5	10	8	10	1	1	
Asterionella	9								5	2	10				
Cyclotella	8							1	25	2	47				
Fragillaria									3		1				
Navicula			2	2	1	1	1	1			4			2	
Nitzchia			2	2	1							58			
Synedra									2	2	3				
TOTALS	19	7	3	3	5	21	1091	18	49	800	1051	1152	411	261	385

HANNAH LAKE 1973	July 31	Aug. 8	Aug. 13	Aug. 20	Aug. 27	Sept. 5	Sept. 11	Sept. 18	Sept. 24	Oct. 1	Oct. 9	Oct. 18	Oct. 22	Nov. 1	Nov. 5
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MYXOPHYCEAE															
Chroococcus		P													
CHRYSOPHYCEAE															
Unid Chrysophyte*			2		6		5	20	3	5	9	11	P	7	6
" Chrysomonad	2	9	3	3	48	1	62	55	5	7	7	48	18	32	23
" Flagellate					5			6				13			
" Green+	55	21	28	16	40	10	10	11	6	9	12	21	38	10	5
CHRYPTOPHYCEAE															
Cryptomonas		1								2				P	
Rhodomonas	2	1	P	1	8	3	7								
CHLOROPHYCEAE															
Chlamydomonas		1	2	2	1	P		3	2	3	2	6	1	4	1
Cosmarium	10	21	9	2		5		6	4	8	4			P	
Oocystis			1	1						1	2		3	5	6
Tetraedron		1							3	P					
DINOPHYCEAE															
Peridinium	42	47	43	35	29	25	5	19	39	42	22		17	9	P
EUGLENOPHYCEAE															
BACILLARIOPHYCEAE															
Cyclotella		1										19			
Eunotia										2	P		2		
Frustulia	4		4		30				4	P	P				P
Navicula						5									
Nitzchia														P	P
TOTALS	116	103	92	60	168	49	89	120	66	79	58	118	79	67	41

* Similar in appearance to Selenastrum (a Chlorophyte)

\+ Similar in appearance to Mougeotia

APPENDIX F - Cont'd....

HANNAH LAKE 1974	16 May	29 May	13 June	27 June	3 July	10 July	25 July	8 Aug.	22 Aug.	5 Sept.	10 Sept.	2 Oct.
Week	1	3	5	7	8	9	11	13	15	17	18	21
MYXOPHYCEAE												
Chroococcus	2											
CHRYSOPHYCEAE												
Dinobryon		499	496	33			1	2	1			
Unid Chrysophyte*	6	25	26	19	1	13	38	174	24	10	11	15
" Chrysomonad	7	7	11	5	1	7	5	27	2	2	9	1
" Green+	34	64	185	253	150	55	13	7		1	1	1
CHRYPTOPHYCEAE												
Rhodomonas	1											
CHLOROPHYCEAE												
Ankistrodesmus						2	1	11				
Chlamydomonas	7	11		10	5	33	16	15	23	1	7	2
Closterium								5				
Cosmarium	22	37	18	68		126	65	124	14	2	3	2
Oocystis				1		1		1			11	
Scourfeldia	28											
Spondylosium							10			1		
DINOPHYCEAE												
Peridinium				30			38	17	25	9	3	23
EUGLENOPHYCEAE												
Euglena			12									
BACILLARIOPHYCEAE												
Asterionella								22				
Cyclotella						27		39				
Diatoma						22						
Eunotia	19											
Fragilaria								10				
Frustulia						25						
Navicula				13			18	4	1	2		
Rhizosolenia								4				
Stephanodiscus	2											
TOTALS	162	643	748	456	157	313	219	473	94	29	35	80

* Similar in appearance to Selenastrum (a Chlorophyte)

\+ Similar in appearance to Mougeotia

LOHI LAKE 1973	9 Aug.	14 Aug.	21 Aug.	28 Aug.	6 Sept.	12 Sept.	19 Sept.	25 Sept.	3 Oct.	10 Oct.	15 Oct.	Liming	23 Oct.	2 Nov.	6 Nov.
Week	2	3	4	5	6	7	8	9	10	11	12		13	14	15
MYXOPHYCEAE															
CHRYSOPHYCEAE															
Dinobryon							3								
Unid Chrysophyte*									P	1				P	
" Chrysomonad	1	2	8	16	5	5	3	8	4	18	5		2	2	1
" Flagellate				6											
" Green+	1	1	2				1						P	1	
CHRYPTOPHYCEAE															
Cryptomonas	8	2	3	38	39	107	30	18	10	9	7				1
Rhodomonas		P	P			5					6				
CHLOROPHYCEAE															
Chlamydomonas	1	3	1		5	11	2	5	1	5	1		1	P	1
Oedogonium										30			9		
Oocystis	36	102	387	442	305	99	2	4	12	56	84			1	
Selenastrum					P						P				
Tetraedron								P							
DINOPHYCEAE															
Peridinium	5	3	43	38	22	43	15	25	27	76	29		1	1	P
EUGLENOPHYCEAE															
BACILLARIOPHYCEAE															
Cymbella						11									
Eunotia									2						
Nitzchia															5
TOTALS	52	113	444	545	378	281	56	60	56	195	132†		13†	5	8

* Similar in appearance to Selenastrum (a Chlorophyte)
\+ Similar in appearance to Mougeotia
† Fungal spores present.
.....Liming

APPENDIX F - Cont'd....

LOHI LAKE 1974	15 May	28 May	12 June	25 June	Liming 5	11 July	23 July	6 Aug.	20 Aug.	4 Sept.	17 Sept.	1 Oct.
Week	1	3	5	7		9	11	13	15	17	19	21
MYXOPHYCEAE												
Chroococcus						1		1				2
Oscillatoria		2		1		18	20	10	1	6		1
CHRYSOPHYCEAE												
Dinobryon	23	31	3	25		207	59	4554	203	99		4
Unid. Chrysomonad	4		4	37		40	29	27	22	39	167	41
" Green+		1		8		28	54	132	135	140	162	141
CHRYPTOPHYCEAE												
Cryptomonas							4			2		1
CHLOROPHYCEAE												
Ankistrodesmus								5				
Chlamydomonas		11					2	3			1	1
Desmidium												1
Oocystis		1		8		1		2			1	2
Tetraedron									4	3	6	2
DINOPHYCEAE												
Peridinium			1	3						25	11	22
EUGLENOPHYCEAE												
Trachelomonas										1		1
BACILLARIOPHYCEAE												
Asterionella						3	3	3				
Closterium						3						
Cyclotella						22		16				
Navicula	2										1	
Nitzchia						2						
Synedra							2	4				
TOTALS	29	46	8	82		330	173	4757	365	327	349	219

+ Similar in appearance to Mougeotia

CLEARWATER LAKE 1973	2 Aug.	9 Aug.	17 Aug.	21 Aug.	28 Aug.	6 Sept.	12 Sept.	19 Sept.	25 Sept.	3 Oct.	10 Oct.	15 Oct.	23 Oct.	2 Nov.	6 Nov.
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MYXOPHYCEAE															
CHRYSOPHYCEAE															
Dinobryon					46	36	14	23				3	8		1
Unid Chrysophyte*			1		P		5	6	P	1	2	24			
" Chrysomonad	1	3	1	2	6	13		3	4	4	3	5	9	9	35
" Flagellate					2		5	P				2			
" Green +	4	4	2	5	9	12	19		45	51	33	5	72	61	41
CHRYPTOPHYCEAE															
Cryptomonas	7	4	23	32	73	6	41	13	19	22	42	132	20	19	41
Rhodomonas	1	P	1	1		1									
CHLOROPHYCEAE															
Chlorococcum															1
Chlamydomonas	P		1	P			P	P	10	5	9		23	4	11
Chlorogonium				2			38	67				92	3		8
Cosmarium							6								
Oedogonium														P	
Oocystis									10	59	57	47	2	2	
Staurastrum				2											
Tetraedron												5			
DINOPHYCEAE															
Peridinium	39	44	45	26	9	53	65	31	23	31	19	19	46	46	48
EUGLENOPHYCEAE															
BACILLARIOPHYCEAE															
Cyclotella												8			
Eunotia			4												
Frustulia	2														
Nitzchia														P	
TOTALS	54	55	78	68	142	121	193	143	111	173	165	342	183	141	187

* Similar in appearance to Selenastrum (a Chlorophyte)

\+ Similar in appearance to Mougeotia

CLEARWATER LAKE 1974	15 May	28 May	12 June	11 July	23 July	6 Aug.	20 Aug.	4 Sept.	17 Sept.	1 Oct.
Week	1	3	5	9	11	13	15	17	19	21
MYXOPHYCEAE										
Chroococcus										1
Oscillatoria	24		11		1	4		1		
CHRYSOPHYCEAE										
Dinobryon	35	1	70	89						2
Mallomonas		3								
Kephyrion				1						
Unid Chrysophyte*							6			
" Chrysomonad	19	1	41	63	75	75	3	18	3	17
" Green+	29	9	57	192	81	177	52	79	19	22
CHRYPTOPHYCEAE										
Cryptomonas	24	15	20	9	9	38	1	15	16	20
Rhodomonas						1				
CHLOROPHYCEAE										
Ankistrodesmus				2						
Carteria			7			10				
Chlamydomonas	1	1	4	14		8		7		1
Desmidium						17				
Mougeotia									5	
Oedogonium									21	
Oocystis					22	3		4	8	26
Staurastrum	6			2						
Tetraedron			7							
Unid Colonies			4							
Xanthidium		7								
DINOPHYCEAE										
Peridinium	4	10	83		9	11	8	46	22	36
EUGLENOPHYCEAE										
Trachelomonas		1	2						1	
BACILLARIOPHYCEAE										
Asterionella				6		15				
Cocconeis						9				
Cyclotella			12	35		157				
Nitzchia						4				
Surirella										4
Synedra						13				
TOTALS	139	49	318	408	200	542	70	170	95	129

* Similar in appearance to Selenastrum (a Chlorophyte)

\+ Similar in appearance to Mougeotia

APPENDIX G

MIDDLE LAKE ZOOPLANKTON 1973/1974 (#'s/m^3)

	1973	July 30	Aug. 8	Aug. 13	Aug. 20	Aug. 27	Sept. 5	Sept. 11	Sept. 18	..25-26..	Sept. 27	....28....	Oct. 1	....3....	Oct. 9	....17....	Oct. 18	Oct. 27	..29-31..	Nov. 1	Nov. 5
	Weeks	1	2	3	4	5	6	7	8		9		10		11		12	13		14	15
A. CLADOCERA	Bosmina	2860	20710	10220	64350	23940	310	590	1680		310		40		70		40	50		320	190
	Alona affinis	20																			
	juveniles	10																			
	Chidorus sphaericus	20	20	30	490	10		70	60		3660		210		10		30	10		40	
B. CYCLOPODA	Cyclopoid Copepodid		90	390	250	10		710	40		70				40		10	20			
	Eucyclops sp.	10																			
	Cyclops vernalis			20	90	30		10	10		40						10	10			
D. NAUPLIUS	Nauplius L.	340	270	1280	8950	560	30	6540	4460		2130		250		10			30			
E. ROTIFERA	Rotifers	30				10	10	70	310		140		80		20		20	140		130	
TOTALS		3290	21270	10660	74130	24560	350	7990	6480		6350		580		150		120	260		490	190

	1974	May 15	May 22	May 29	June 5	June 13	June 20	June 27	July 3	July 11	July 15	July 25	July 31	Aug. 8	Aug. 15	Aug. 20	Aug. 29	Sept. 5	Sept. 10	Sept. 18	Sept. 25	Oct. 2	Oct. 9	Oct. 15	Nov. 14
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A. CLADOCERA	Bosmina	16		19	94	63	27			815	379	33	286	397	620	64	139	189	55	189	90	260	699	55	504
	Chidorus sphaericus							27		24	33		38	37	16	8	41	8	39	24	75	23	255	134	78
B. CYCLOPODA	Cyclopoid Copepodid			19		220	108	81	24	24	25	8	23	18	169	282	57	32							
	Cyclops vernalis						189	81			16	8			8	48	24	8	307	205	53	78	1712	820	87
	C. bicuspidatus Thomasi																							15	
C. CALANOIDA	Calanoid Copepod															1410	115	8	87	296	7				
D. NAUPLIUS	Nauplius Larvae															16			7			7	82	15	7
TOTALS		16		38	94	283	324	189	24	853	453	49	347	452	813	1828	376	245	495	716	225	368	2748	1039	676

Sample missing

..... denotes liming

APPENDIX G - Cont'd...

HANNAH LAKE ZOOPLANKTON 1973/1974 (#'s/m)

	1973	July 31	Aug. 8	Aug. 13	Aug. 20	Aug. 27	Sept. 5	Sept. 11	Sept. 18	Sept. 24	Oct. 1	Oct. 9	Oct. 18	Oct. 22	Nov. 1	Nov. 5
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A. CLADOCERA	Bosmina	60	1330	70	2320	260	130	760	760	170	100	380	170	90	430	50
	Chidorus sphaericus	140	230	220	230	50	140	50	20	70	410	10	80	80	50	
	Acantholeberis curvirostris						10									
	Ceriodaphnia megalops								10							
B. CYCLOPODA	Cyclopoid copepodid		10		50			10	20		20	20	40	50	20	
	Cyclops vernalis											10		50	10	
D. NAUPLIUS	Nauplius Larvae	570	120	1360	420	160	660	1080	810	760	170	160	170	160	130	
E. ROTIFERA	Rotifers							400	960	620	290	100	120	150	160	
TOTALS		770	1690	1650	3020	920	940	2300	2580	1620	990	680	580	530	800	50

		May 15	May 22	May 29	June 5	June 13	June 20	June 27	July 3	July 11	July 18	July 25	July 31	Aug. 8	Aug. 15	Aug. 20	Aug. 29	Sept. 5	Sept.10	Sept.18	Sept.25	Oct. 2	Oct. 9	Oct. 15	Nov 14
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A. CLADOCERA	Bosmina	63		14	14	28	28	14		2006	407	42	1430	1023	2707	294	291	140	84	98	154	419	189	27	108
	Chidorus sphaericus	21						14	84	84	70	42	112	42	126	84	247	84	84	168	266	69	148	243	94
B. CYCLOPODA	Cyclopoid Copepodid		20		270	196	154	113	140	196	14		14	28	42	70	29	14	42	42	56	13	94	378	40
	Cyclops vernalis	21			140	70	56	42	42	154	14	56		28		196		14	42	42	56	13	94	378	40
	C.bicuspidatus Thomasi																				14				
C. CALANOIDA	Calanoid Copepodid															3703	116	70	224	182					
	Epischura lacustris																		56						
D. NAUPLIUS	Nauplius Larvae		20	14	14											70			28	14			13		
TOTALS		105	40	28	438	294	338	183	266	2440	505	140	1556	1121	2875	4417	683	308	518	504	490	501	444	648	255

APPENDIX G - Cont'd....

LOHI LAKE ZOOPLANKTON 1973/1974 (#'s/m^3)

	1973	July 31	Aug. 9	Aug. 14	Aug. 21	Aug. 28	Sept. 6	Sept. 12	Sept. 19	Sept. 25	Oct. 3	Oct. 10	Oct. 15	....16....	Oct. 23	Nov. 2	Nov. 6
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12		13	14	15
A. CLADOCERA	Bosmina	68230	31330	71490	62570	25250	13660	25880	13140	8430	8310	3040	25890		40	40	360
	Chidorus sphaericus	270	480	240	320	460	130	60	120	140	440	80	60		30	30	40
	Ceriodaphnia megalops	10	20		10	40	10		10		10						
B. CYCLOPODA	Cyclops vernalis	50	40	110	50	150	140	60	90	60	330	460	540		30	10	40
	Cyclopoid copepodid	170	70	80	150	770	940	460	220	540	1610	2660	1510		60	40	60
D. NAUPLIUS	NaupliusLarvae	1790	14080	10240	8050	14060	7780	18850	3540	6950	9280	9270	2480		110	50	10
E. ROTIFERA	Rotifers	10	10	20	310	11740	55170	77650	74950	53740	9940	8160	17890		70	50	
TOTALS		70980	45990	82180	71460	52470	77830	122,440	92070	69870	27980	23670	48370		310	220	510

	1974	May 15	May 23	May 28	June 4	June 12	June 18	June 25	July 3	....5.... July 9	July 16	July 23	July 30	Aug. 7	Aug. 13	Aug. 20	Aug. 29	Sept. 4	Sept. 11	Sept. 17	Sept. 24	Oct. 1	Oct. 8	Oct. 15	Nov. 14
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A. CLADOCERA	Bosmina	165	86	84	12	86	54	419	1010	2925	1757	4060	3757	2554	6847	234	2131	601	12	2540	456	1815	36	331	1035
	Chidorus sphaericus							20	16	52	24	6	96		54		36	6	24	24	96	18	474		29
	Ceriodaphnia megalops												6								30				
B. CYCLOPODA	Cyclopoid Copepodid						67	135	63	84	47	24	90	66	12	18	97	18							
	Cyclops vernalis	6					20	95	16	116	41	36		36	18	36	134	78	114	198	96	18	42	17	88
	C. bicuspidatus Thomasi																		6	12	24	6			
	Mesocyclops edax																		6	12					
C. CALANOIDA	Calanoid Cyclopoid															258	513	12	42	613	6				
	Epischura lacustris															6									
D. NAUPLIUS	Nauplius Larvae		12				7					12					6							5	
TOTALS		171	98	84	12	86	148	669	1105	3167	1869	4138	3949	2656	6931	552	2917	715	204	3399	708	1857	552	353	1152

..... denotes liming

APPENDIX G - Cont'd....

CLEARWATER LAKE ZOOPLANKTON 1973/1974 (#'s/m)

	1973	July 31	Aug. 9	Aug. 14	Aug. 21	Aug. 28	Sept. 6	Sept. 12	Sept. 19	Sept. 25	Oct. 3	Oct. 10	Oct. 18	Oct. 23	Nov. 2	Nov. 6
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A. CLADOCERA	Bosmina	2350	2000	16440	4920	10600	20100	18880	2650	1750	1790	1630	1430	1060	4410	3160
	Chidorus sphaericus	110	290	40	60	10	30	40	10	40	210	30	60	80	110	150
	Alona affinis	20														
	Ceriodaphnia megalops	110	10		10	10	10	10	10	10	10					
B. CYCLOPODA	Cyclopoid Copepodid	130	10	220	50	290	170	230	150	190	180	280	190	60	40	60
	Cyclops vernalis				20	30	30	10		10	20	40	50	10	10	10
D. NAUPLIUS	Nauplius larvae	160		3580	180	1170	1330	1620	820	2070	1720	450	530	160	120	140
E. ROTIFERA	Rotifers					10	950	900	1840	1280	240	140	280	10	10	2130
TOTALS		3060	2040	20280	5240	12120	22620	21690	5480	5350	4170	2570	2540	1470	4700	5650

	1974	May 15	May 25	May 28	June 4	June 12	June 18	June 25	July 3	July 9	July 16	July 23	July 30	Aug. 7	Aug. 15	Aug. 20	Aug. 29	Sept. 4	Sept. 11	Sept. 17	Sept. 24	Oct. 1	Oct. 8	Oct. 15	Nov. 15
	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A. Bosmina		6	80	217	11	18	106	1274	12110	30874	25713	46790	63235	52609	28508	38925	28063	*	37460	17000	2244	19630	5936	18768	+
C. sphaericus					6	6	30	26	26	17	226	217	334	211	77	122	221	54	27	111	84	11	117	124	216
Acantholeberis curvirostris													5		44										
C. megalops												11	16	11	5	5	21	5		5				21	21
B. Copepodid				22	183	325	1007		155	327	186		38	27	22	22									
C. vernalis					71	278	1230		155	249	158	61	61	66		105	129	27	66	122	50	91	149	454	119
C.b. Thomasi																				33	5		16	16	10
C. Copepodid																167	297	21	22	300					
E. lacustris																11									
D. Nauplius L.			11	17		12	24				6	5								5					
TOTALS		6	80	234	39	290	763	3537	12446	31467	26289	47084	63689	53013	28656	39357	28731	**	37575	17576	2385	19732	6218	19303	++

* 37104: ** 37211 + 8548: ++ 8914

APPENDIX H

PARAMETER \ LAKE	MIDDLE		HANNAH		LOHI		CLEARWATER	
YEAR	1973	1974	1973	1974	1973	1974	1973	1974
A. # Accepted Hauls	30	22	29	50	25	38	26	40
B. Area Sampled/Haul (cm^2)	232.3	522.6	232.3	522.6	232.3	522.6	232.3	522.6
C. Total Area Sampled (cm^2) A X B	6969.0	11497.2	6736.7	26130.0	5807.5	19858.8	6039.8	20904.0
D. Total # Organisms In All Samples	456	111	790	3110	637	849	636	11146
E. Adjusted Total Number of Organisms/m^2, Tot. Adjusted = $\frac{10,000(D)}{C}$ (Rounded to Nearest #) 10,000 cm^2 = 1m^2	654	96	1172	1190	1096	427	1053	5331

Number and Parameters of macro Benthic Data Collected 1973 and 1974 on Reclamation Lakes. Experimental Lakes marked with (*).This Appendix provides data used in Figure .

Lake / Parameter	MIDDLE*				HANNAH				LOHI*				CLEARWATER			
Year	1973 Aug. 15-17		1974 Aug.		1973 Aug. 15-17		1974 Sept.		1973 Aug. 15-17		1974 Sept-Oct.		1973		1974 Oct. 3-10	
Parameter	Total No.	%	Total No.	%	Total No.	%	Total No.	%	Total No.	%	Total No.	%	Total No.	%	Total No.	%
Number of Accepted Hauls/Samples.	30		22		29		50		25		38		26		40	
DIPTERA Chironomidae	414	90.8	99	89.2	766	96.9	2989	96.1	548	86.0	375	44.1	589	92.6	10949	98.2
Pupae							77	2.4			6	0.8			12	0.1
Chaoberidae			1	0.9							30	3.5				
Ceratopogonidae									1	0.2					2	.01
MEGALOPTERA Sialidae	34	7.5	10	9.0	14	1.7	14	0.5	7	1.1	17	2.0	22	3.5	102	0.9
OLIGOCHAETA					7	1.0			61	9.6	404	47.6	20	3.1	62	0.6
TRICHOPTERA Psychomyiidae	7	1.5	1	0.9	3	0.4	19	0.6	5	0.8	3	0.4	2	0.3	7	0.06
ODONATA Libellulidae							3	0.1	9	1.4	8	0.9	1	0.2	9	0.08
Coenagrionidae	1	.2					8	0.3	6	0.9	4	0.5	2	0.3	1	0.01
LEPIDUPTERA Pyralididae											2	0.2			2	0.12
TOTALS+	456	100.0	111	100.0	790	100.0	3110	100.0	637	100.0	849	100.0	636	100.0	11146	100.0
TAXA	4		3		4		5		7		8		6		8	
+adjusted to #/m^2	654		96		1172		1190		1096		427		1053		5331	

APPENDIX I

Summary of Chemical Parameters in Lohi Lake Enclosures

		pH	Alkalinity	Hardness	Conductivity	Ca	Mg	Cl	Na	K	SO_4	Turbidity	Ni	Zn	Cu	Fe	Pb	Mn	Co	Cd	Al	Si
C-1	$\bar{y}$	6.6	2.3	25	75	8.0	1.2	1.4	1.5	1.0	26.1	.93	.20	.038	.059	.083	.015	.265	.008	.001	.321	3.1
	n	9	9	8	9	8	8	8	7	7	8	6	6	6	6	6	5	6	5	3	6	9
C-2	$\bar{y}$	6.4	2.5	25	75	8.0	1.2	1.4	1.5	1.0	23.5	1.15	.20	.029	.044	.233	.015	.249	.006	.001	.291	3.0
	n	11	11	10	11	10	10	10	10	10	10	7	6	6	6	6	5	6	5	3	6	10
N-1	$\bar{y}$	6.4	2.4	25	75	8.0	1.2	1.4	1.5	.10	25.7	.76	.21	.033	.045	.069	.012	.251	.007	.001	.208	3.1
	n	11	11	10	11	10	10	10	10	10	10	7	7	7	7	7	6	7	5	4	7	10
N-2	$\bar{y}$	6.4	2.5	25	75	8.0	1.2	1.4	1.5	1.0	25.7	.94	.21	.033	.042	.134	.008	.252	.007	.002	.163	3.0
	n	11	11	11	11	10	9	10	10	10	10	8	5	5	5	5	5	5	4	2	4	10
P-1	$\bar{y}$	6.5	2.4	25	75	8.0	1.2	1.4	1.5	1.0	25.7	.99	.23	.035	.055	.116	.010	.267	.008	.002	.227	3.2
	n	11	11	10	11	10	10	10	10	10	10	8	7	7	7	7	7	7	6	4	6	10
P-2	$\bar{y}$	6.5	2.5	25	75	8.0	1.2	1.4	1.4	1.0	25.8	.99	.22	.033	.051	.105	.010	.260	.007	.001	.195	3.2
	n	11	11	10	11	10	10	10	10	10	10	8	7	7	7	7	7	7	6	4	7	10
S-1	$\bar{y}$	6.6	2.7	25	75	8.1	1.2	1.4	1.4	1.0	25.0	1.28	.22	.036	.056	.210	.012	.266	.008	.001	.306	2.7
	n	6	6	5	6	5	5	4	5	5	5	4	5	5	5	5	5	5	5	3	5	7
S-2	$\bar{y}$	6.5	2.7	25	75	8.0	1.1	1.4	1.4	1.0	25.9	1.28	.21	.032	.043	.121	.008	.256	.007	.001	.196	3.3
	n	11	11	10	11	10	10	9	10	10	10	8	7	7	7	7	6	7	6	4	7	10
Background in Lohi Lake		6.2	2.2	24	75	7.8	1.2	1.5	1.5	1.0	25.7	.65	.19	.030	.042	.05	-	.245	-	-	.149	3.5
		23	23	23	23	23	22	21	23	23	23	10	12	11	11	11	-	12	-	-	11	23

C = control
N = nitrogen added
P = phosphorus added
S = sewage added

$\bar{y}$ = mean value
n = number of samples

APPENDIX J

TUBE ZOOPLANKTON NUMBERS /m^3 - LOHI LAKE (1974)

	C1			C2				Background Lake Levels			
	Sept.12	Sept.18	Sept.23	Sept.12	Sept.18	Sept.23	Oct. 7	Sept.11	Sept.17	Sept.24	Oct. 7
CLADOCERA											
Bosmina longirostris	256	13		67	67		81	12	2540	456	36
Chidorus sphaericus	973	2096	2001	1203	2596	4639	162	24	24	96	474
Ceriodaphnia megalops	81	1352	595	229	121	162	13			30	
CYCLOPODA											
Copepodid				135							
Cyclops vernalis	256	229	419	595	1176	1704	148	114	198	96	42
CALANOIDA											
Copepodid	27	162	13	13	148			42	613	6	
Epischura lacustris											
NAUPLIUS L.				27	67	40					
TOTALS	1593	3852	3028	2269	4175	6545	404	192	3375	684	552

APPENDIX J - Cont'd..

	N2				P1				P2				S2			
	Sept. 12	Sept. 18	Sept. 23	Oct. 7	Sept. 12	Sept. 18	Sept. 23	Oct. 7	Sept. 12	Sept. 18	Sept. 23	Oct. 7	Sept. 12	Sept. 18	Sept. 23	Oct. 7
CLADOCERA																
Bosmina longirostris	40			54	54				148				4409			
Chidorus sphaericus	473	6384	5815	1866	1853	6614	10685	5802	2853	6329	5775	3557	11036	12930	9792	8331
Ceriodaphnia megalops	94	7641	3476	243	1136	1704	4328	365	121	1041	919	284	1109	148	2137	94
CYCLOPODA																
Copepodid																
Cyclops vernalis	81	568	676	229	216	243	243	175	216	284	365	162	405	121	392	202
CALANOIDA																
Copepodid	13	27			27	108			13	67	13		175	13		
Epischura lacustris													13			
NAUPLIUS L.																
TOTALS	701	14593	9967	2392	3286	8669	15296	6342	3381	7721	7072	4003	17147	14173	12321	8627